TECHNICAL REPORT
NATICK/TR-11/004

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ELECTRO-OPTIC FABRICS FOR THE WARRIOR OF THE 21ST CENTURY
PHASE II

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January 2011

Final Report
November 1999 - November 2002

Approved for public release; distribution is unlimited.

Prepared for
U.S. Army Natick Soldier Research, Development and Engineering Center
Natick, Massachusetts 01760-5056

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*: 20-01-2011

2. REPORT TYPE: Final

3. DATES COVERED *(From - To)*: November 1999 - November 2002

4. TITLE AND SUBTITLE
ELECTRO-OPTIC FABRICS FOR THE WARRIOR OF THE 21ST CENTURY--PHASE II

5a. CONTRACT NUMBER: DAAD16-99-C-1016

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Patricia Nguyen and Jeremiah Slade

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Foster-Miller, Inc.
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Waltham, MA 02451-1196

8. PERFORMING ORGANIZATION REPORT NUMBER
NLB-990238-1662

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Natick Soldier Research, Development and Engineering Center
ATTN: RDNS-SP (C. Winterhalter)
Kansas Street, Natick, MA 01760-5056

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
NATICK/TR-11/004

12. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Expiration of SBIR Data Rights Period: July 2008

14. ABSTRACT
Report developed under Small Business Innovation Research contract. The overall objective of this Phase II effort was to develop and deliver a prototype "smart" garment system that contains an electrical/electro-optical network in the form of appliquéd narrow woven buses which assist, rather than hinder, the soldier in completing his assigned mission. A key aspect of Foster-Miller's approach to meeting this objective was to assure that the network was designed from the outset using fightability and wearability principles, i.e., to assure that the smart uniform neither degrades the soldier's ability to fight nor to perform normal operational tasks while wearing it. Numerous concepts for electro-optic cables, connectors, wireless power transfer methods and network design were generated and evaluated in this program. The use of narrow woven cable was found to form a robust, low risk, low weight solution to a soldier borne personal area network (PAN).

15. SUBJECT TERMS

CABLES	WEARABLE	ELECTROOPTICS	ELECTROTEXTILES
FABRICS	DETECTION	ELECTRIC CABLES	SMART TECHNOLOGY
TEXTILES	FLEXIBILITY	ARMY PERSONNEL	WEARABLE COMPUTING
WEAVING	PROTOTYPES	DATA TRANSMISSION SYSTEMS	
UNIFORMS	CONNECTORS	HUMAN FACTORS ENGINEERING	
GARMENTS	SBIR REPORTS	PAN(PERSONAL AREA NETWORK)	
NETWORKS	LIGHTWEIGHT		

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
U	U	U	SAR	156	Carole Winterhalter
					19b. TELEPHONE NUMBER *(include area code)* (508) 233-5460

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ELECTRO-OPTIC FABRICS FOR THE WARRIOR OF THE 21ST CENTURY-PHASE II

1. SUMMARY

1.1 Program Objectives

The overall objective of the Phase II effort was to develop and deliver a prototype “smart” uniform that contains an electrical/electro-optical network in the form of appliquéd narrow woven buses which assist, rather than hinder, the soldier in completing his assigned mission.

A key aspect of Foster-Miller’s approach to meeting this general objective was to assure that the network was designed from the outset using fightability and wearability principles, i.e., to assure that the smart uniform while being worn neither degrades the soldier’s ability to fight nor to perform normal operational tasks. This effort was straightforward but essential in order to assure military acceptance.

To accomplish these goals, the program was divided into the following eight tasks:

- Task 1 – Review Fightability Results and Design Network.
- Task 2 – Bus Development and Testing.
- Task 3 – Connector and Node Development and Testing.
- Task 4 – Non-Connected Interface Development and Testing.
- Task 5 – Network Integration and Testing.
- Task 6 – Refine Network Design.
- Task 7 – Build, Test and Deliver Prototype Network.
- Task 8 – Reporting.

1.2 Conclusions

1.2.1 Cable Design and Material Selection

USB 2.0 is the preferable standard for soldier borne personal area networks as it permits high data rate, ad-hoc reconfigurability with hot swapping capabilities.

In the near term, copper-based electrotextile data cables are preferable to electro-optic cables. This advantage is due to the commercial, logistical and safety concerns associated with implementing an optical network.

Replacing the Aluminum/Mylar shielding used in standard USB cable designs with a braided shielding made from electrotextiles provides several advantages, including better shielding effectiveness, increased flexibility and extended flex life.

Testing revealed that nylon webbing can withstand considerable loading, fatigue and wear-related abuse if a sufficiently tight structure is used. Woven cables are therefore preferable to braids.

Stiffness testing results showed that standard electro-optic components contribute a significant portion to the overall cable stiffness. Several methods of decreasing the stiffness of these components were identified:

- Use of softer, lower durometer, insulations on all wires.
- Use of highly stranded conductors.
- Replacement of the standard foil shielding with a hollow braid of metal clad fibers.

1.2.2 Safety Issues

Short chopped stainless steel and/or nylon fibers generated during trimming may come in contact with the skin or become airborne and get into the respiratory system depending on the local airflow. This situation has been found to cause limited irritation in some individuals. To reduce these effects, it is recommended that the denier of the individual nylon filaments be changed if MIL-SPEC allows to reduce the potential for skin irritation from short coarse fibers. In addition, the remedial coating procedure taken by Malden Mills to protect the stainless steel yarn should be used in future weavings to limit fiber breakage. It is also recommended that when trimming or post-trimming to length the narrow wovens, all persons wear the following safety equipment:

- Gloves.
- Safety glasses.
- Lab coats.

During any trimming operations, either a dust mask or a suction airflow should be used at the station to avoid breathing the fibers into the respiratory system.

1.2.3 Connector Overmold

Connector interfaces should be rectilinear. Most commercial connectors are round in profile and scale fast in dimension when the number of pins increases. An overall flat and rounded edge profile is most appropriate for body-borne connectors that are on the torso.

The plug-in motion of a lap-top PC type connector is not ideal for body-borne use. The plugging motion requires that the cable leave the plane of the clothing, requiring extra material for the plugging action. A snapping or sliding motion should be investigated.

While the premold/overmold concept worked well in this program, it is labor intensive. Future work should investigate monolithic mold designs.

When selecting an overmolding material, care should be taken that its injection temperature does not exceed that of the wiring insulation or shorting may occur. If a low-temperature overmolding material is not available, the molding material should not come into contact with any exposed wires. Prepotting or premolding the wires with a lower temperature barrier material is an effective technique for protecting the insulation.

An adequate number of positioning pins should be included at the outset of mold design to prevent cable washout and textile showthrough.

1.3 Brief Background

Today's complex geo-political climate has forced the U.S. armed services into new operational strategies. The prevalence of international terrorism, the threat from chemical and biological weapons, the "three-block" operational mission, and economic pressure to reduce the size of the active force has placed increasing demands on the military. Clearly, the services are driven to "do more with less."

An outgrowth of these pressures has been the development of concepts such as the 'battle force,' the 'vertical battlefield,' and the 'digitized soldier.' Each of these concepts relies on rapidly redeployable troops having enhanced decision-making capability brought about through rapid transfer and dissemination of information to each member of the squad. Tactical Internet (TI) provides the means to distribute this information to the soldier on the battlefield. What is missing is the ability to process and use this information via an intranet at the level of the individual soldier for the benefit of the squad. For example, if a chemical weapon sensor were intranetted to the radio, it could relay a signal to other squad members to don protective clothing, thereby enhancing unit survivability.

Systems and devices to gather information (e.g., laser target identifier, GPS, CBW sensors, Combat ID) are either part of the current soldier system or under development. However, a network to link these devices on the body and to facilitate inter-communication of this key information without hindering military operations is lacking. Therefore, this Phase II program focused on the development of this crucial networking technology.

A more specific objective of the Phase II effort was to develop and deliver a prototype "smart" uniform that contains an electrical/electro-optical network in the form of appliquéd narrow woven buses which will assist, rather than hinder, the soldier in completing his assigned mission. A key aspect of Foster-Miller's approach to meeting this objective was to assure that the network is designed from the outset using fightability and wearability principles, i.e., to assure that the smart uniform neither degrades the soldier's ability to fight nor to perform normal operational tasks while wearing it. This effort was straightforward but essential in order to assure military acceptance.

Information on fightability and wearability was obtained from a number of sources. Foremost among these sources was the Arthur D. Little study for the Army's Natick RD&E Center (NRDEC) on fightability and the Carnegie-Mellon study for DARPA on wearability.

This information was combined with Phase I results and other information to provide the technology base for design, fabrication and testing of a textile-based, general personal area network that will connect devices. At the end of the Phase II program, three to five demonstration systems containing the network applied were delivered to the Government for independent testing.

Several key issues regarding integration into a textile needed to be addressed in carrying out the approach to meet the general objective. These included:

1. Integrating washable wires and plastic optical fibers into a narrow woven system to be applied to the garment. The system must be rugged, washable, lightweight, flexible, EMI-shielded and must operate when wet.

2. Connecting lines within the network at node points. An example is a bus running down the arm connecting to the main bus which flows along the body torso. These connection points may require overmolded junctions; they may also contain opto-electronic hardware to convey electrical signals to the optical network or routing chips.

3. Connecting external devices to the network. Here, two different classes of devices would have to be integrated: 1) devices not connected to the body (large battery packs, computers, etc.), and 2) other devices that connect to the uniform (e.g., small sensors, fabric-based antenna). These connections require fresh hybrid design rules specifying how to go from textile to device. Again, the connections have to operate in the military environment.

4. Transferring data and/or power across non-connected interfaces (e.g., from pants to coat, from sleeve to glove). Transformers are strong candidates for this job because of the wet operation issue. Body-based transformers already exist (manufactured by Plastics One) but may require some modification for this application.

Specific objectives for the Phase II program are:

- Determine hybrid (textile-device) design rules for future network development and wearable device integration.

- Design, fabricate and evaluate an electrical or electro-optical network which is fabric-based and which has the potential to function in a military environment.

- Select connectors and related components for the network. If necessary, modify them to assure they are sufficiently robust for the military environment.

- Perform a laboratory evaluation of the potential to transfer power across non-interconnected interfaces in the uniform.

- Build demonstration wearable networks which withstand a minimum of three washings (with a target of 20 washings), operate when damp or surrounded by water, and fulfill fightability requirements.

- Deliver three to five prototype garments to the Government in medium/regular size with the network including representative nodes and connectors applied.

2. PROGRAM TASKS

The overall objective of the Phase II effort was to develop and deliver a prototype “smart” uniform that contains an electrical/electro-optical network in the form of appliquéd narrow woven buses which will assist, rather than hinder, the soldier in completing his assigned mission.

A key aspect of Foster-Miller’s approach to meeting this general objective was to assure that the network is designed from the outset using fightability and wearability principles, i.e., to assure that the smart uniform neither degrades the soldier’s ability to fight nor to perform normal operational tasks while wearing it. This effort was straightforward but essential in order to assure military acceptance.

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3. TASK BY TASK DESCRIPTION OF ACCOMPLISHMENTS

3.1 Task 1 - Review Fightability Results and Design Network

Task 1 was divided into three areas of study: 1) A review of fightability/wearability studies, 2) the design of general networks, and 3) assessment of the fightability of the network design. As will be discussed in the following paragraphs, this program was initiated and completed during one of the most significant periods of system re-design for the soldier. The impact of concurrent design efforts (Land Warrior, Scorpion, and OFW) on the planned execution of Task 1 was significant. The OFW and Scorpion design efforts show that network design must take into account the larger system issues and rely on the interaction of many factors such as ballistic protection, load carriage equipment, quick don-doff requirements, and electronic component and feature needs. Early in the Phase II program, Foster-Miller and the Army realized that the system design targets (i.e., Land Warrior versions) were rapidly evolving and that minor changes in the system architecture had large consequences to this program's goals and execution. As an example the implementation of the computer system on the Battle Dress Uniform (BDU) or in a Modular Light-Weight Load carrying Equipment (MOLLE) vest greatly changes the technical requirements for a textile network. Therefore, after several months of evaluating possible network architectures that could be relevant to the soldier system, an early decision was made to focus on the technology development aspect of the Phase II program and de-emphasize the network design aspect of the program as this was a fast moving target and more appropriate to a larger system effort.

The following sections detail the work and decisions that were made which pertain to network design and architecture. Because of the decoupling of Task 1 from Tasks 2 to 7 as discussed above, Task 1 work was completed during the entire program and was refined with respect to concurrent programs such as Land Warrior, Scorpion, and OFW.

3.1.1 Review Fightability and Wearability Results

Early in the program, an on-site review of the Design for Wearability conducted by Carnegie Mellon University was held in Pittsburgh. An examination of preferred sizes and locations for devices was reviewed. Foster-Miller negotiated a long-term borrowing of the physical representation of the "pods" from Carnegie Mellon University (CMU) to allow networking discussions and brainstorming.

One of the important pieces of data used early in the Design for Wearability study is a map of locations where buttons and pockets are commonly placed (Figures 1 and 2). These form early bounds on locations were devices can be stowed for accessibility and help show where

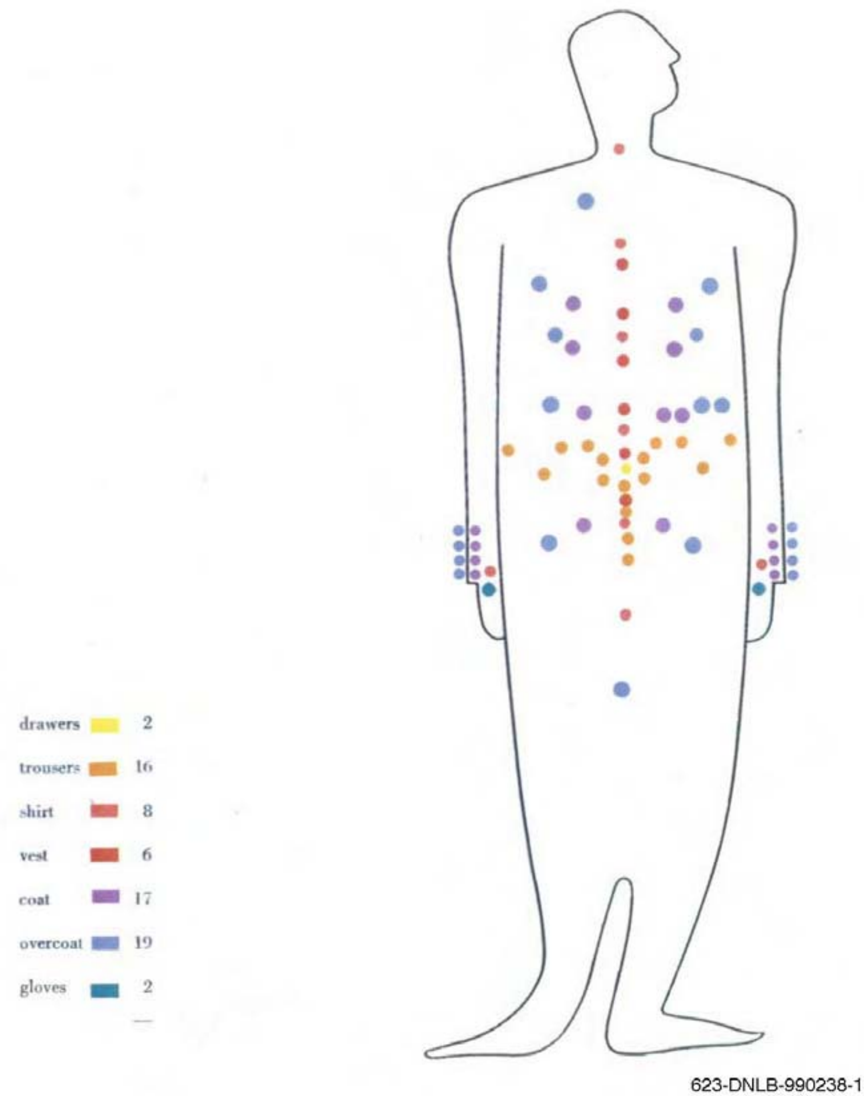


Figure 1. Map of common button locations (figure courtesy of CMU)

networking should be centered. This data was taken as one piece of the puzzle, since the soldier has different constraints than the typical individual on clothing use.

A similar assessment of the results of the Fightability Study by Arthur D. Little (ADL) was made. An important differentiator between the CMU study and the ADL study was the target audience. The CMU study looked for the solution space that would allow for the largest objects in locations on the body that would go unnoticed by the common business person daily. This bounded the optimal physical space and connectivity map. The ADL study looked for the physical space that could be occupied on the human that did not interfere with their ability to do a limited set of the integrated movement techniques for soldiers. There was some limited assessment of weights in different locations also. The work was assessed against current configurations. To maximize the synergy between the CMU and ADL studies, Foster-Miller Inc. hosted a large brainstorm meeting with attendees from Foster-Miller, the Army, ADL and CMU. The main conclusions of this study were that:

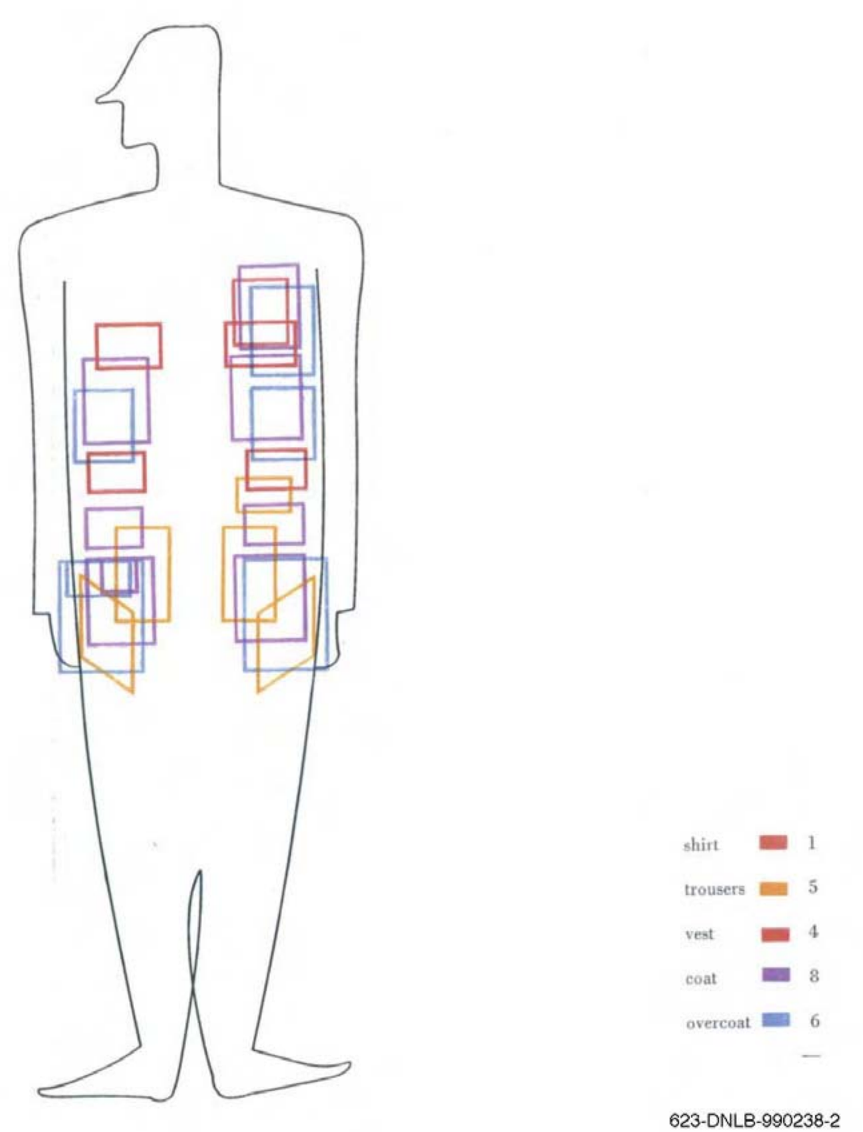


Figure 2. Map of common pocket locations (figure courtesy of CMU)

- A complete Personal Area Network (PAN) for military applications will need to include both a skin level network for monitoring the user's physiological status and a garment level system for routing power and data between devices such as the MILES system, GPS modules, CBW sensors, and Combat ID systems.
- The skin level network will need to be routed such that sensors can be collocated with major organs and critical portions of the circulatory system.
- The garment level network will need to be routed following the recommendations of the CMU study (2).

- The skin level and garment level networks will ideally need to communicate with one another. Given that the two networks will need to follow different paths it may be necessary to investigate methods for transmitting power and data across non-connected interfaces.

3.1.2 Design General Networks

Discussions with the United States Army Research Institute of Environmental Medicine (USARIEM) revealed that any physiological network carried added Food & Drug Administration (FDA) approval burden above and beyond other performance requirements. FDA regulations are such that if the physiological network is too entwined with the communications and data networks, then all the networks would be deemed medical devices. We determined to separate the physiological and non-physiological networks to ensure that the entire soldier ensemble not be labeled a medical device. Further discussions with USARIEM, the Warrior Systems Integration Team, and the Contracting Office's Technical Representative led us to decide to focus on the non-physiological network in this Phase II program.

Discussions with Andy Taylor of Natick and Jack Tyrell of Exponent identified a potential soldier system application which could be easily networked using the Phase II cables for demonstration purposes. Exponent is currently manufacturing and delivering a set of new MILES (Multiple Individual Laser Engagement System) prototypes for training purposes. The new system incorporates an improved sensor network. As the cables on the system either use a USB protocol or a protocol that is inherently similar in cable design to the USB cable, they suggested that we could provide cables for integration. Full details of this work are provided in subsection 3.5.

3.1.3 Assess Fightability of Network Design

The aspects of the network which most effect fightability are:

- Projection of cables away from the body resulting in a snag hazard.

- Stiffening of otherwise flexible clothing resulting in limitation of range of motion.

- Size, shape, and mechanism of the connector units which promote failure.

- Interaction with other electronic units on the body, i.e., antennas, which could effect performance.

The form factor and low stiffness of the webbing reduces the risk of projection from the body. Projection does become an issue depending on the system which the network is integrated into. Early MOLLE vest systems which Foster-Miller worked with had an upper body vest which was attached to belt by adjustable slides and webbing. To accommodate different sizes, as we tried to integrate cabling into the system, additional cabling had to be added which could cause snagging if not attached flush with the vest/belt system. Many potential connectors were

brainstormed to obviate the problem. None were ideal because they introduced another potential failure point in the system and required a substantial cross section to perform their function.

Mid-program, a modified MOLLE load carriage vest was introduced which reduced the number of adjustable interfaces and improved the situation but did not solve the problem entirely. The problem of projection was significantly reduced during the Scorpion and OFW programs when the entire soldier system was redesigned using integration of a network as one of the large number of driving factors. We learned that consolidation of the network onto a limitedly adjustable one-piece “chassis” could reduce the number of nodes, routing, and potential projection of the network cables and connectors. This type of design was able to fully take advantage of the benefits of the textile based cable network without introducing other negative artifacts caused by using a support structure that was never intended to house a network.

Stiffness was a factor which was well investigated in the technical portion of the program. Early in the program the thrust of electronic-textiles was to use them as either a replacement for a piece of clothing or as an appliqué on a piece of clothing, such as a BDU. With this thought in mind, the stiffness of a narrow woven cable would need to closely replicate that of the uniform to maintain the freedom of motion and reduce discomfort. As is discussed in detail in subsection 3.2.2.2, Foster-Miller developed a protocol to measure stiffness which was used to measure progress towards this goal. During the program, close replication of the cable textile properties to a webbing without any electrical elements was achieved. But replication of the drape of a BDU fabric was not seriously attempted. This was because during the first six months of the program, the Land Warrior architecture was modified from the Raytheon based system to Land Warrior 0.6 which relied on the MOLLE vest and helmet as a stand-alone support system for the electronic architecture. The MOLLE load carriage system uses webbing primarily for its construction, prompting a decision in the Phase II program to focus on webbing implementations of the network which were appropriate to outer layer use, a decision which was further supported by ARIEM which was focusing on wireless systems for inner layer networks at the time. Because of the overall stiffness of the MOLLE system and its location on the body, the stiffness of the cable was not expected to effect fightability unless it deviated dramatically from a typical webbing property.

Fightability is not only the ergonomics of the system, but the ability of the system to function during use. Connector reliability is a large factor in system function during a soldier’s mission. As will be discussed in length in subsection 3.3, Connector Development and Testing, reducing the profile of the connectors and the actual mechanism action are important to reliability and fightability. During brainstorming meetings several significant conclusions about connectors were reached. They include:

- Connector interfaces should ideally be rectilinear. Most environmentally sealed connectors currently have a round profile. As the number of pins is increases the diameter of the connector can increase rapidly. A rectilinear profile on the other hand can scale to become wider without becoming thicker, thereby making it the more ergonomic solution.

- The plug-in motion of a lap-top Personal Computer (PC) type connector is inappropriate for body-borne use. The plugging motion requires that the cable leave the plane of the clothing, requiring extra material for the plugging action. A snapping or sliding motion should be investigated.

- An overall flat and rounded edge profile is most appropriate for body-borne connectors that are on the torso.

Because the technical development during this program had to focus on the cost effective demonstration of connectors, standard off-the-shelf connectors were used. Commercial of the Shelf (COTS) connectors were made compatible with Foster-Miller's textile cables by means of overmolding the two together. The results of these efforts, outlined in subsections 3.3 and 3.5, combined with the conclusions of fightability discussions resulted in the recommendation that significant investment in connectors would be required for the soldier system. This investment is needed regardless of which type of network, textile or other, is incorporated.

One important realization that came out of discussions with BAE Systems on a different contract (3) was the importance of interaction between the various subsystems on the body. The presence of an electronic network and placement of electronic "boxes" will affect antenna systems on the body and must be considered as part of the design of the PAN if a body borne antenna is to be used. A separate electrical network will also act as an antenna in the presence of a working antenna and cause interference. Therefore, the power network should ideally be routed through the same electrotextile structures used for the antenna system feeds and radiators. Concepts that will allow the integration of the network and antenna system such that unwanted interference with the antenna will be avoided are needed. The direction which was given to the OFW program as an outlet from this Phase II was to assume that the entire electronics systems (communications, computer, network, power, and antennas) will be integrated into one layer in a single garment. The outermost layer of the garment would incorporate the antenna with its feeds and/or radiators being used as the power network (and data if electrical and not optical conductors are used). The electronic "boxes" would then need to be in a layer of the garment closer to the body to avoid interference with the antenna when it is hooked into the network, or alternatively, the antenna would require testing/design to minimize the performance degradation.

The important conclusion is that the PAN network cannot be designed without affecting the other subsystems on the body. To have an effective network design, it must be designed in concert with the antennas, electronics and ammunition placement, ballistics and load bearing ensemble systems, and helmet system. Each system must give and take to result in the best use of the new textile network technology.

3.2 Task 2 - Bus Development and Testing

An extensive breadth and depth of work was done on this task. It included an investigation of textile compatible transmission media, communication protocols, implementation and fabrication methods, and testing and evaluation. The following sub-index describes the topics covered in this section:

- 3.2.1 Cable Development
  - 3.2.1.1 Evaluation of Work Done in Phase I
  - 3.2.1.2 Investigation of Candidate Electro-Optic Materials
    - 3.2.1.2.1 Electrical Wire Selection
    - 3.2.1.2.2 Optical Fiber Selection
  - 3.2.1.3 Protocol Survey
    - 3.2.1.3.1 USB Protocol Review
    - 3.2.1.3.2 IEEE 1394 Protocol Review
    - 3.2.1.3.3 Gigabit Ethernet Protocol Overview
  - 3.2.1.4 Implementation of the USB Specification
    - 3.2.1.4.1 USB Version 1 (USB v1)
    - 3.2.1.4.2 Preliminary Evaluation of USB Version 1
    - 3.2.1.4.3 USB Version 2 (USB v2)
    - 3.2.1.4.4 USB Version 3 (USB v3)
  - 3.2.1.5 Implementation of IEEE 1394 Specification
  - 3.2.1.6 Skin Irritation Issues
- 3.2.2 Cable Testing
  - 3.2.2.1 Mechanical Abrasion and Wear
  - 3.2.2.2 Stiffness
  - 3.2.2.3 Tensile Strength
  - 3.2.2.4 Tensile Fatigue
  - 3.2.2.5 Bending Fatigue
  - 3.2.2.6 Impact Testing

3.2.1 Cable Development

3.2.1.1 Evaluation of Work Done in Phase I

This section is intended to give a brief overview of the work done on the Phase I program only. The specific details regarding test procedures, results and conclusions can be found in the Phase I final Report (4).

In the Phase I portion of this program, our subcontractor, C.M. Offray & Sons (now Offray Specialty Narrow Fabrics (Watsontown, PA)), fabricated a narrow woven bus using nylon yarns as specified by MIL-STD-W43668. This standard was also used as the baseline for the weave structure with the exception that electrical and optical transmission media were included in the stuffer layers. The bus contained a sheathed 250µ plastic optical fiber with 1 Gb/sec data rate capacity and seven highly flexible insulated tinsel wire conductors for transmitting power or data. The conductor wires were made up of seven individual tinsel wires and had a resistance of 0.003 Ω/cm. Testing of the cable developed in Phase I was undertaken to provide a performance baseline for the materials used and to provide guidance in the design of cables for the Phase II portion. This baseline highlighted areas where additional development was needed. Of primary concern at this stage were abrasion resistance and environmental effects. Offray subjected four pieces of cable to hex abrasion testing. This process is described in greater detail in subsection 3.2.2.1, Mechanical Abrasion and Wear. The cables were subjected to 1000, 2000, 3000, and

4000 cycles. The resistivity of the individual wires was measured and compared to that of a non-abraded wire and a wire which had not been incorporated into the textiles. As a summary, the resistivity of the tinsel wire did not increase with the cyclic abrasion, although the textile itself showed significant wear and distortion. The resistivity of the wire remained the same within the error bars of the measurements.

Wash and humidity testing was carried out in which two BDU fabric panels were fabricated with eight insulated tinsel wires and one strip of the Phase I bus affixed to each panel. The resistivities of the individual wires were measured and recorded before being capped with electrical tape and then epoxy to prevent water ingress through the ends of the wires. One of these fabric panels was placed into a humidity chamber at Foster-Miller at 80°C and 80 percent relative humidity. The fabric was exposed to 12 days under these conditions. When the fabric sample was removed and tested its resistivity was found to have remained unchanged.

The second fabric sample was sent to Natick to be washed under modified AATCC Test Method 96-1997 Test IVc. Several of the end caps came off during the first wash cycle. The sample was returned to Foster-Miller for repair. Before repair, the other end-caps were removed and the resistivities measured. The resistivities did not change. The ends were recapped with a better epoxy and the sample returned to Natick for further washing. The samples were washed an additional five times. The end caps were removed after the sample was returned to Foster-Miller and the resistivities were measured. The average change in resistivity was less than 1 percent. The high was an increase of 5 percent in resistivity. There was no apparent trend between the low and high frequency measurements (25 Hz to 1 MHz).

3.2.1.2 Investigation of Candidate Electro-Optic Materials

Foster-Miller has been developing a broad technology base for integrating electrical and optical networks, devices and other components directly into garments and fabrics. We have demonstrated the application of textile-based antenna radiators and textile-based electrodes in an electromyography (EMG) monitor that matches the response of the standard EMG electrodes. As a result of these research programs and the work done on this Phase II electro-optic textiles program, Foster-Miller has completed a survey of materials that are conductive and potentially compatible with textile and garment fabrication processes. Descriptions of these materials are provided in Table 1 while Table 2 shows some representative conductive textile structures.

3.2.1.2.1 Electrical Wire Selection

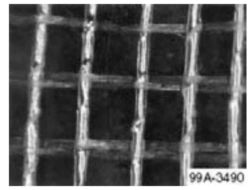
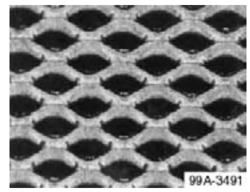
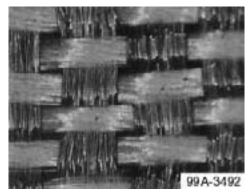
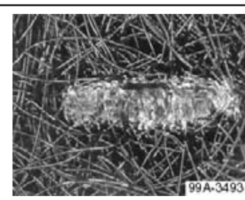
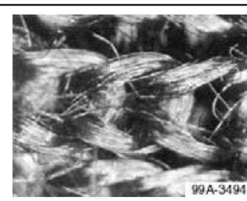
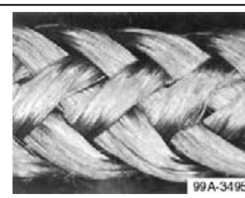
In the Phase I program, tinsel wire was down selected as the most suitable power and electrical data transmission lines. Plastics One, Foster-Miller's overmolding subcontractor, currently produces a wide variety of tinsel wire products specifically for wearable harnesses. A tinsel wire cable is made up of:

- The core fiber which is wrapped by bands of metal ribbon. This core fiber is usually polyester or Kevlar® for high load conditions.

Table 1. Conductivity of conductive textile based fibers

Type	Name/ ID	Yarn Denier	Yarn Diameter	Weight	Resistance	Comments
		g/9000 m	inch	lb/1000 ft	ohm / 1000 ft	
Bench Mark Conductors	Solid Copper Wire: 22 gauge	26010	0.025	1.95E+00	1.61E+01	Low resistance but stiff
	Solid Copper Wire: 28 gauge	6480	0.013	4.84E-01	6.49E+01	
	Solid Copper Wire: 30 gauge	4077	0.010	3.04E-01	1.03E+02	
	Solid Copper Wire: 36 gauge	1017	0.005	7.57E-02	4.15E+02	
Bekaert Continuous S.S. Filament Yarns	VN 14/1x90/100z/316L	1000	0.0052	7.47E-02	2.10E+04	Good handalability and washability.
	VN 14/2x90/175S/316L	2000	0.0074	1.49E-01	1.10E+04	
	VN 14/2x275/175s/316L	6210	0.0131	4.64E-01	3.00E+03	
	VN 12/1x275/100z/316L	2250	0.0079	1.68E-01	8.00E+03	
	VN 12/2x275/175S/316L	4500	0.0111	3.36E-01	5.00E+03	
	VN 12/3x275/175S/316L	6750	0.0136	5.04E-01	3.00E+03	
Bekaert Spun Yarns	BK 50/1 80PES / 20SS 500Z	180	0.004	1.34E-02	1.74E+06	High resistance and poor durability
	BK 50/2 80PES / 20SS 565S	360	0.005	2.69E-02	8.84E+05	
	H54/1 88Nylon / 12SS 520Z	167	0.004	1.25E-02	1.02E+07	
Aracon Metal Clad Aramid Fibers	XN0400E-018	400	0.012	9.34E-02	1.00E+03	Handles well due to stiff aramid core but has poor washability. The denier refers to the aramid fibers before metallization.
	XN0200E-025	200	0.008	4.70E-02	2.80E+03	
	XN0400EF-018	400	0.012	1.24E-01	7.00E+02	
	XS0400E-018	400	0.012	9.34E-02	1.00E+03	
	XS0200E-025	200	0.008	4.70E-02	2.80E+03	
	XS0400F-040	400	0.012	1.36E-01	7.00E+02	
X-Static Silver Coated Nylon	40011	23	NA	1.72E-03	3.66E+06	Nylon coated with silver. Handling breaks silver coating, increasing resistance.
	40030	40	NA	2.99E-03	6.10E+05	
	40064	85	NA	6.35E-03	2.44E+05	
Montgomery Tinsel Wire	T3889	10748	0.0319	8.03E-01	2.11E+02	Durable and washable. Used in telecommunications industry.
	T3610	38045	0.054	2.84E+00	5.00E+01	
Metallized Mylar Thread	DMC Gold	NA	NA	NA	2.13E+03	Metallized Mylar core. Handling breaks thin film, increasing resistance.
	Sulky Gold	NA	NA	NA	4.27E+09	
	MegaSheen Gold	NA	NA	NA	3.02E+05	
Carbon Fibers	Badishe 21/1	140	NA	NA	3.44E+09	Very high resistance

Table 2. Illustration of conductive textile structures

Type of Textile Structure	Picture
Copper-Silk Organza Silver-coated copper wrapped fiber woven with silk	
Copper Foil Flexible copper foil structures with well defined pore sizes	
Silver Fabric Narrow woven made from silver coated continuous nylon fibers	
Silver Felt Silver coated nylon chopped fiber fabricated as a felt	
Stainless Steel Knit Knit fabric from 100% stainless steel continuous filaments	
Stainless Steel Cord Braided cord from 100% stainless steel continuous filaments	
Stainless Steel Fabric Fabric woven from 100% stainless steel continuous filaments	

489-P-99711-6

- The metal ribbon which can be copper, copper or brass plated with silver, or stainless steel.

- A jacket material such as Polyvinylchloride (PVC), Teflon®, or silicone. The jacket thickness and material determine the water penetration, flexibility, and durability.

- An additional shielding wrap of tinsel wire and a final jacket if necessary.

Changes to this standard tinsel wire cable that could achieve the required flexible, washable wire include the following:

- Metallurgical content of conductive overwrap can be changed. Wires used in this program had a silver content of 1.5 percent. If necessary this silver content can be increased to extend lifetime of washed wire. New conductive combinations of metals are currently under development to address deficiencies of copper (corrosion) and silver (debonding).

- Conductivity can be increased by going from a single band to a double band configuration and can be further affected by increasing the width of the wrap sheet.

- Flexibility of shielded wire can be increased by using stainless steel thread (Bekaert) or silver coated nylon (Sauquoit Industries) wrapping instead of tinsel wire as the shielding material.

While tinsel wire was successfully demonstrated in the Phase I program it was felt that the electrical wire selection process should be reexamined in this Phase II effort. To that end electrical wires made from standard stranded copper and Aracon® were also considered.

Standard copper wires are not typically thought of as being flexible or textile compatible but do offer other advantages such as low cost and compatibility with all wire and data transmission standards. For these reasons alone standard copper conductors were felt to be worth further consideration. It was also recognized that by constructing wires using a larger number of high gauge (small diameter) filaments it might be possible to increase the flexibility of such wires significantly.

Aracon® is a relatively new product, available only from DuPont™. It combines the conductivity of an outer metal coating with the strength, light weight and flexibility of aramid fibers. Aracon® fibers are based on the same technology that created DuPont™ Kevlar®, well known for its use in bullet-resistant vests, high-speed boats and military helmets. With the addition of nickel, copper and silver coatings of varying thicknesses, Aracon® fibers provide a versatile combination of physical and electrical properties for a variety of applications. Aracon® metal clad fibers have been evaluated in a number of applications where the strength, flexibility and light weight of the aramid base and the electrical conductivity of the metal cladding provide unique advantages in solving engineering problems. Two applications that stand out as excellent opportunities for the unique properties of Aracon® fibers are EMI shielding and electrotextile

conducting. Washability tests conducted on a separate program (3) however indicate that after just ten cycles of dry cleaning or washing, Aracon® experiences significant loss of its metal coatings resulting in very low surface conductivity readings. As a result may need to be insulated if repeated washability is a requirement.

3.2.1.2.2 Optical Fiber Selection

Optical fiber can be used to great advantage in the data interconnect bus structure of future smart clothing. Optical transport of data can take place at rates in excess of 1 Gb/s without excessively complex electronics. These data rates are quite sufficient to handle any predicted data interconnection requirements for Land Warrior systems.

Two materials systems for optical fiber are in use today, glass and plastic. While glass fibers have been optimized for use in the telecommunications industry, the extremely large bandwidths and operational distances capabilities of this type of optical fiber are not necessary for the smart fabric application. The distance requirements are moderate for smart fabric applications (<5m) and the possibility of incurring complications to a wound by the presence of fine glass fiber fragments following a penetration make the choice of plastic optical fiber for this application logical. The diameters of optical fiber available (2 mm to 0.25 mm) and the bend radius tolerance (1 mm without breakage for a 2 mm diameter fiber) allow it to be used in flexible clothing situations.

In the Phase I effort (4) the weaveablity, flexibility, washability, and general ruggedness of a plastic optical fiber produced by Boston Optical Fiber (Westborough, MA) was evaluated when woven within a fabric appliqué. The optical fiber contained Kevlar® fiber protective strands within the jacket that improve the strength of the optical fiber but allowed good flexibility. Another key requirement is that the optical fiber should not easily burn. The optical fiber used in Phase I tests (P6R-FB250) was approximately 0.25 mm in diameter and was jacketed with a Union Carbide low combustible polymer, DFDA-1638, that passes Navy requirements for smoke index (NES-711), toxicity (NES-713), and critical temperature index (NES-715). It also passes the ASTM-E662 test for smoke density and IEC-754-2 for acidity of combustion products. The outer diameter of the jacketed optical fiber was approximately 0.762 mm. Further details can be found in the Phase I final report (4).

Since plastic optical fiber can support many of the data and signal transport protocols and data rates utilized in telecommunications, antenna remoting, and local area network (LAN) applications over the short distances involved in garments, it is best to select a fiber that is very flexible in the type of uses that it supports and one that enjoys wide-spread commercial applicability. Unfortunately, the use of plastic optical fibers is held back today by the lack of optical connectors.

3.2.1.3 Protocol Survey

In this Phase II effort several transmission standards were investigated in an initial survey. These included USB Revision 2.0, IEEE (Institute of Electrical & Electronics Engineers) 1394b

Draft 1.00, and Gigabit Ethernet. Of particular interest was selecting a standard that permitted transmission over a variety of media including standard copper and Plastic Optical Fiber (POF).

During initial meetings with Natick, these data protocols were discussed as candidates for incorporation into the narrow wovens. Two of these standards were then downselected by the Army as being of the most use, USB 2.0 and IEEE-1394. It was then decided that the USB protocol would be implemented in a standard copper conductive media while the IEEE 1394 would use POF. While the generic network had not been designed at this point, we determined that many of the important technical issues could be explored by fabricating a prototype for the Universal Standard Bus. A *narrow woven* webbing was chosen as the textile implementation for the USB cable because it had the potential to be easily integrated into the MOLLE system in the short term. We chose the USB standard for initial development over the IEEE-1394 for several reasons:

- IEEE-1394, and other standards choices such as coax, are more sensitive to shielding and physical factors (diameter, etc.).

- USB is a standard in wide use today for personal computers, whereas IEEE-1394 is just beginning to be used. Therefore, prototypes could be more immediately used by the military and in commercial applications.

- Evaluation of the performance of data transfer over plastic optical fibers would be difficult.

3.2.1.3.1 USB Protocol Overview

The USB is a cable bus that supports data exchange between a host computer and a wide range of simultaneously available peripherals (Figure 3). The attached peripherals share USB bandwidth through a host-scheduled protocol. The Universal Serial Bus (USB) Specification describes the physical bus attributes, the protocol definition, types of transactions, bus management, and the programming interface required to design and build systems and peripherals. The original motivation for the USB came from three interrelated considerations; connection of the PC to the telephone, ease of use, and port expansion. The more recent motivation for the USB Revision 2.0 stems from the fact that PCs have increasingly higher performance and are capable of processing vast amounts of data. At the same time PC peripherals have added more performance and functionality. User applications such as digital imaging require a higher performance connection between the PC and the peripherals. USB Revision 2.0 addresses this need by adding a third transfer rate of 480 Mb/s to the 12 Mb/s and 1.5 Mb/s originally defined for USB.

3.2.1.3.2 IEEE 1394 Protocol Overview

The P1394b draft standard details the cables, connectors and signaling protocol necessary for a high performance serial bus. The cables outlined in this standard typically consist of a pair of power wires and two parallel physical connections which continuously transmit data. Several

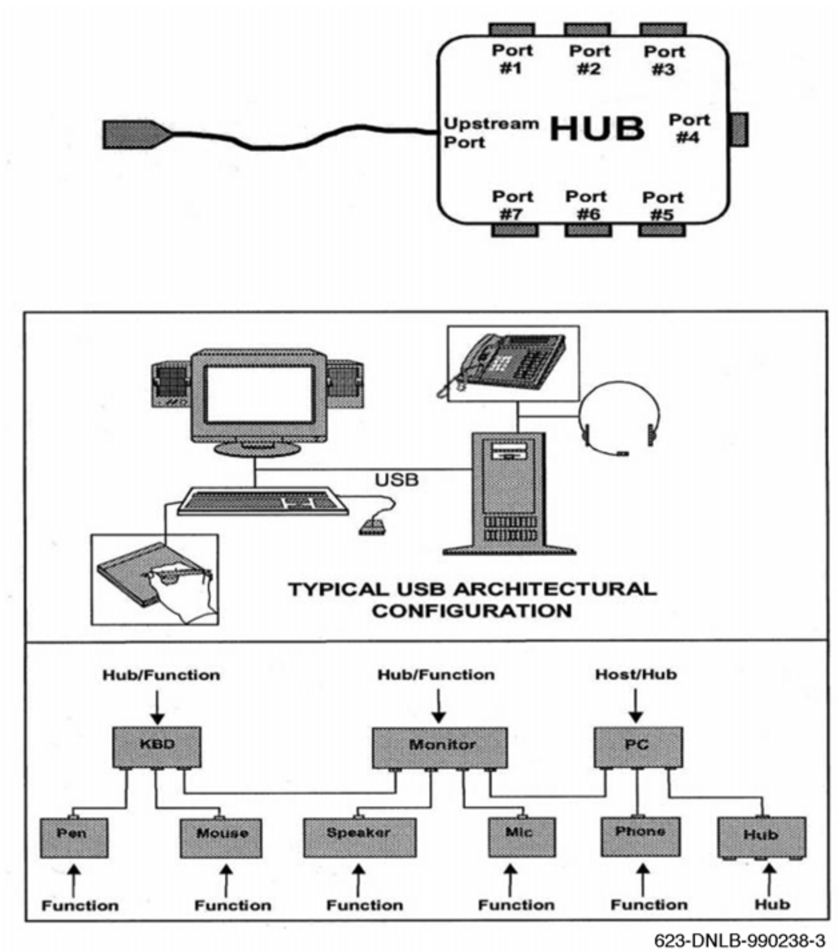


Figure 3. Typical USB architectural configuration

options are available for the data transmission media: Shielded Twisted Pairs (STP), Category 5 Unshielded Twisted Pairs (UTP5), Multi Mode glass optical Fiber (MMF), Plastic Optical Fiber (POF) and Hard Polymer Clad Fiber (HPCF). The max transmission distance and available bus speeds associated with each of these modes of data transfer are shown in Table 3. It should be noted however that for POF and HPCF the maximum transmission distance is dependent on the number of fiber-to-fiber connections within the cable as shown in Table 4.

3.2.1.3.3 Gigabit Ethernet Protocol Overview

Gigabit Ethernet is an extension to the highly successful 10 Mb/s and 100 Mb/s IEEE 802.3 Ethernet standards. While providing a raw data handling bandwidth of 1000 Mb/s it still

Table 3. Summary of data transmission media options

		Bus Speed (Mbits/s)				
Media	Reach	S100	S200	S400	S800	S1600
UTP5	100m	x				
POF	50m*	x	x			
HPCF	100m*	x	x			
MMF	100m			x	x	x
STP	4.5m			x	x	x

Table 4. Tradeoff for the number of connections and transmission length

No. of Connections	Total POF Connection Length	Total HPCF Connection Length
0	50m	100m
1	42m	96m
2	34m	50m
3	27m	4m

maintains full compatibility with older Ethernet installations. It retains the Carrier Sense Multiple Access/Collision Detection (CSMA/CD) technique as the access method and supports full duplex or half duplex modes of operation. As such it is a simple protocol to implement and for contained networks, such as a fully equipped war fighter, will provide extremely broad band, high speed communications between nodes. It will also allow simple interconnection to commonly used computer local area networks (LANs). In this way, the war fighter himself may be simply networked by either a radio or "hard connection" Ethernet link to other resources.

Gigabit Ethernet 1000Base-X optical fiber standard is based on the Fiber Channel Physical Layer, an interconnection technology finding applicability today in connecting workstations, supercomputers, storage devices and peripherals. The lowest two layers FC-0 (interface and media) and FC-1 (encode/decode) are used in Gigabit Ethernet.

3.2.1.4 Textile Implementation of the USB Specification

3.2.1.4.1 Important Characteristics and Components of the USB Specification

The USB bus can operate at three speeds. High speed (480 Mb/s) and full speed (12 Mb/s) require the use of a shielded cable with two power conductors and a twisted signaling pair also known as the data pair (Figure 4). Low speed (1.5 Mb/s) recommends, but does not require the

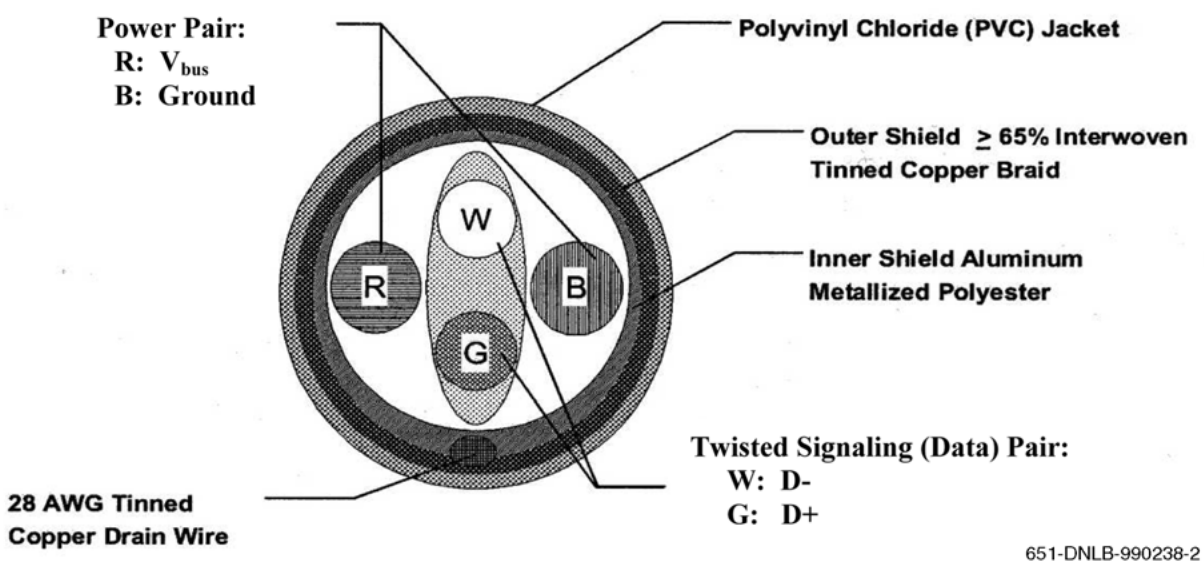


Figure 4. Construction of a standard USB 2.0 cable

use of a cable with twisted pair signal conductors. USB uses a “keyed connector” protocol which permits three types of connectors: “A,” “B” and “mini B” (Figure 5). The “A” connector is the principal means of connecting USB devices directly to a host or to the downstream port of a hub. All USB devices must have the standard Series “A” connector detailed in the specification. The “B” and “mini B” connectors allow device vendors to provide a standard detachable cable. This specification also describes three classes of cable assemblies: standard detachable cable, high/full-speed captive cable, and low-speed captive cable. A standard detachable cable is a high/full-speed cable that is terminated on one end with a series “A” plug and terminated on the other end with a series “B” or “mini-B” plug. A high/full-speed captive cable is terminated on one end with a series “A” plug and has a vendor specified connect means (hardwired or custom detachable) on the opposite end for the peripheral. The low speed captive cable is the same as the high/full-speed captive cable but may only be attached to low speed peripherals. Any other cable assemblies are prohibited.

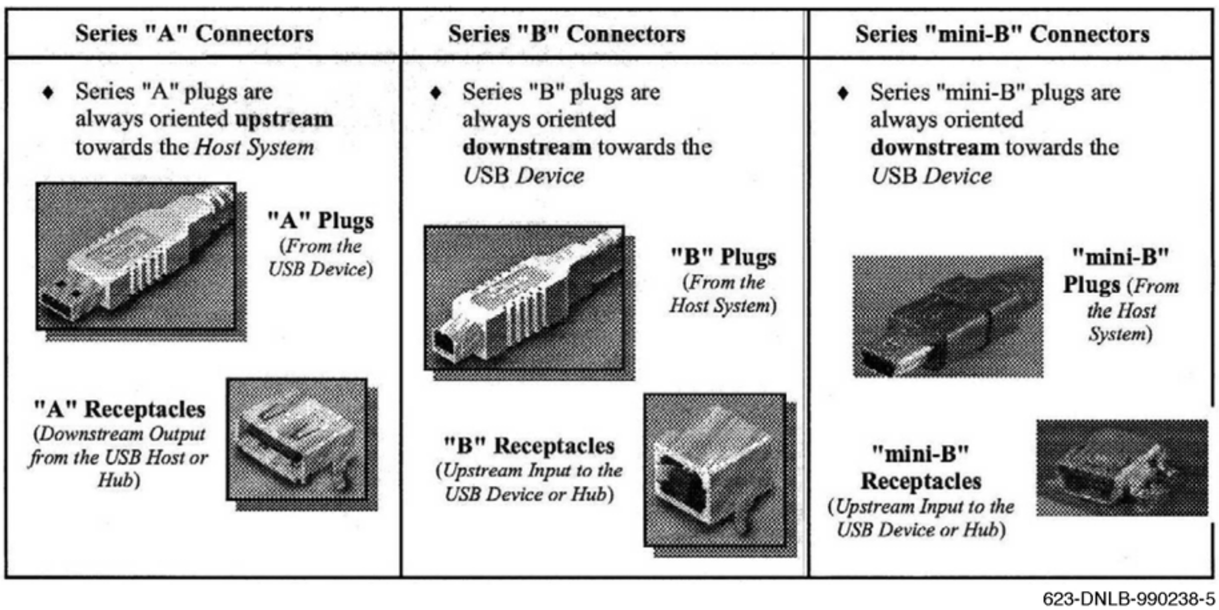


Figure 5. USB 2.0 connector types

3.2.1.4.2 Design of a Textile USB Cable (Version 1)

After examination of the USB specification, two potential designs for a narrow woven cable were conceived (Figure 6). In the first design the power wires were placed on either side of the shielded twisted pair. The possibility of using a non-twisted pair where the data wires were widely separated, as shown in the second design, was also considered.

In both cases the braided shielding called for in the USB 2.0 standard was to be replaced by continuous stainless steel fibers in the weave and stuffer layers. The foil and stainless steel shielding was only to be used around the data wires since the power wires do not require shielding. The foil shield was to consist of an aluminum metallized polymer such as polyester or Mylar® wrapped (served) around the data wires.

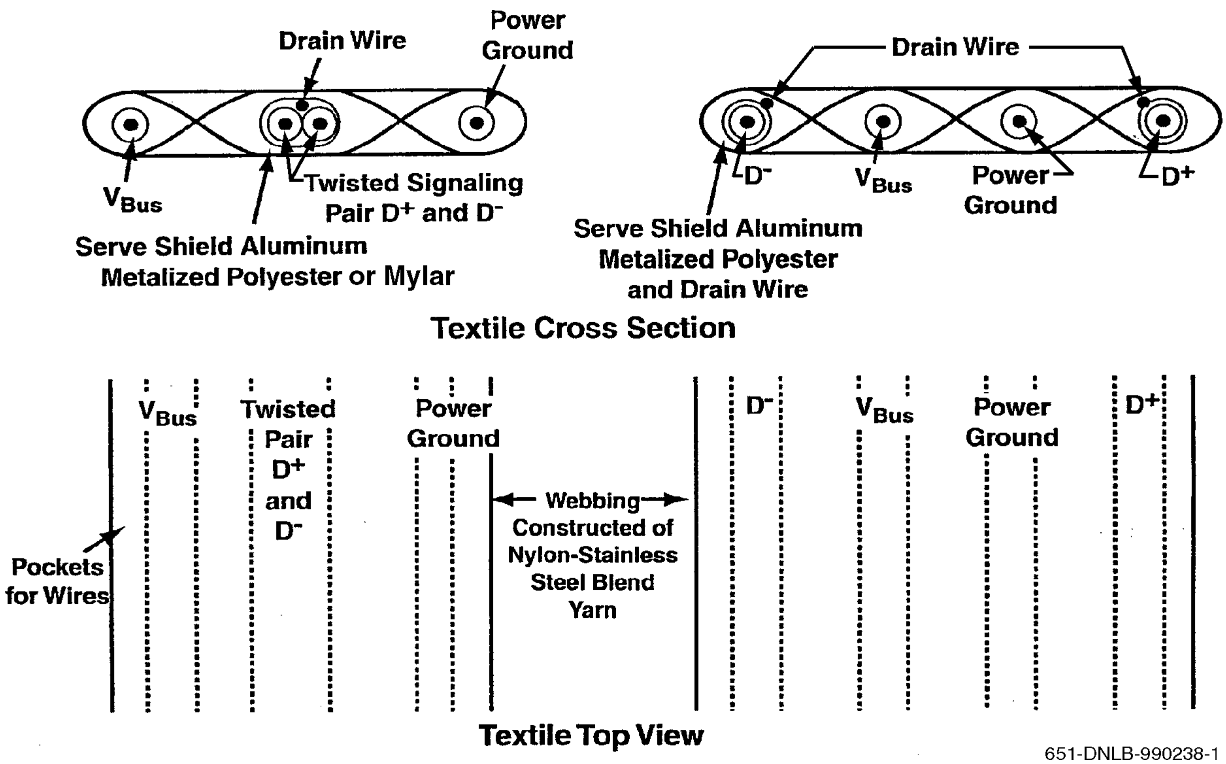


Figure 6. Early designs considered for flat textile cable

Early in the program, Foster-Miller visited Offray at its specialty products plant in Williamsport, PA. During this visit details of the webbings to be produced were discussed. Foster-Miller was taken on a detailed plant tour to understand the entire weaving process by looking at the needle looms which would be used to fabricate the prototypes. This first-hand look was necessary for the Foster-Miller staff to understand more completely the flexibility of the equipment and the material requirements (i.e., wires on spools, etc.). During the discussion, the USB standard was explained and the conceptual designs were discussed.

We decided that the first version of the textile USB cable would adhere to the revision 2.0 specification as much as possible. The goal was to essentially disassemble a standard USB cable and integrate the functional elements into a narrow woven textile format. The elements of this textile cable would include:

- *Signal Pair:* Twisted 28 AWG (American Wire Gauge) PVC insulated wire wrapped foil shielding.
- *Foil Shielding:* Aluminum metallized Mylar® or polyester foil for low frequency shielding.
- *Power Pair:* 20 AWG stranded tinned copper with PVC insulation.
- *Drain Wire:* 28 AWG un-insulated drain wire in contact with aluminum jacket of signal pair.

- *100 percent Stainless Steel Fiber:* For high frequency shielding purposes.

- *Fill Yarn:* Nylon/steel yarn.

With the exception of the high frequency stainless steel shielding, this construction contained the same components as the traditional USB concentric design. The principle difference was that the components were laid out in a flat arrangement with the shielded signal pair located between the power pair conductors. The textile portion of the USB cable was a double plain weave using 22 pics/in. of a 1260 denier olive drab nylon yarn. To facilitate unraveling of the webbing to expose the wires for connectorization, the design also incorporated a catch cord on one side of the webbing. The data and power pairs were embedded in the stuffers of the fabric during the weaving process. The center section of the webbing had stainless steel threads dispersed in the nylon yarn on both faces of the fabric and in the stuffer position at both edges of the shielded center section. Inside the foil shielded center section were the twisted pair and a drain wire. The twisted pair and the drain wire were in the same stuffer channel to maintain constant contact the length of the webbing.

Several additional changes to the cable standard were considered to accommodate manufacturing, cost, weight, or abrasion issues. These design modifications included:

- The twisted data pair was wrapped (served) with aluminum metallized Mylar® shielding by the wire manufacturer. The drain wire was not integrated by serving around the twisted pair, but instead laid in next to the data pair as part of the warp.

- Offray also asked if the twists per inch of the twisted pair could be increased to make it a more round cross-section. The twisted pair would feed over mandrels more easily under those conditions. Upon investigation at Plastics One and Foster-Miller, increased twists per inch were determined to increase the overall impedance of the wires, reducing the length for which the USB spec was valid to a length unusable on the body (less than 1 ft). Therefore, the specified twists per inch were used in the cable.

- The data and power wires would be more closely located in the center of the webbing cross-section. This configuration would allow the shielding to be contained in a center stripe down the middle of the webbing. By consolidating the shielding, to be made from 100 percent stainless steel filament yarns, weight could be saved and the cost reduced. In addition, the non-shielding warp yarns would be MIL-SPEC green nylon filament yarn, resulting in a grey stripe down the middle of the webbing identifying it as a cable and providing indications where stitching can occur without damage to the wires.

The first version of the USB cable had problems with the power wires poking through the weave and exhibiting "waviness" along the wire channel. Some examples of this behavior are shown in Figure 7. Offray reported that the power wires and main data carrying cable were drawn over a rod to create a bend. When bending over the bar, the effective length of wire that was being drawn changed because of the difference in diameters of each wire. Therefore, excess power wire was being fed into the pockets, causing it to become wavy and occasionally poke

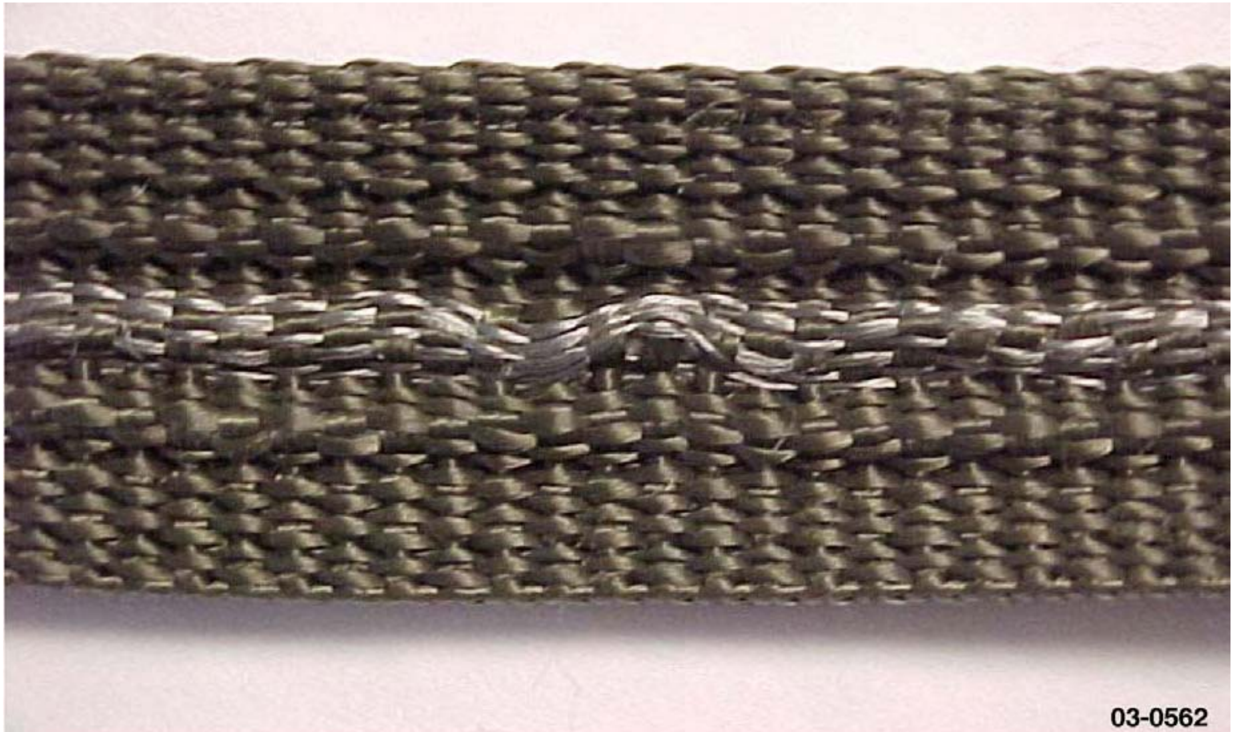


Figure 7. First iteration of USB v1 cable showing waviness in the cable pocketing and shielding

through the webbing. To remedy this issue, a notch was cut into the rod so that the center of the larger diameter cable would travel along the same distance as the smaller power wires. After this modification the narrow woven USB v1 cable was noticeably smoother in appearance (Figure 8). There were still obvious problems with poke-through of the power wires, however.

3.2.1.4.3 USB Version 1 Cable Evaluation

Evaluation of the Foster-Miller narrow woven USB v1 cables for compliance with standards specification EIA Publication 364, USB 2.0 was performed by Contech Research (Attleboro, MA). Contech Research specializes in connection and interconnect technology and testing. They have been intimately involved in the finalization of USB cable and connector specifications, and have a correspondingly detailed knowledge of the contents of the class specs. George Olear, the Mechanical and Environmental Test Engineer, was responsible for all USB testing work done at Contech Research. A preliminary phone discussion with Mr. Olear yielded valuable information about which types of testing were likely to be required in order to have our textile cable rated as USB complaint. One important point that was made by Mr. Olear was that environmental testing such as salt water spray would be pointless given our decision to use USB connectors, which are by definition not environmentally sealed. He suggested that we limit our evaluation techniques to Group 6 signal integrity testing and EMI shielding effectiveness testing. The data from these tests can be found in Appendix A.

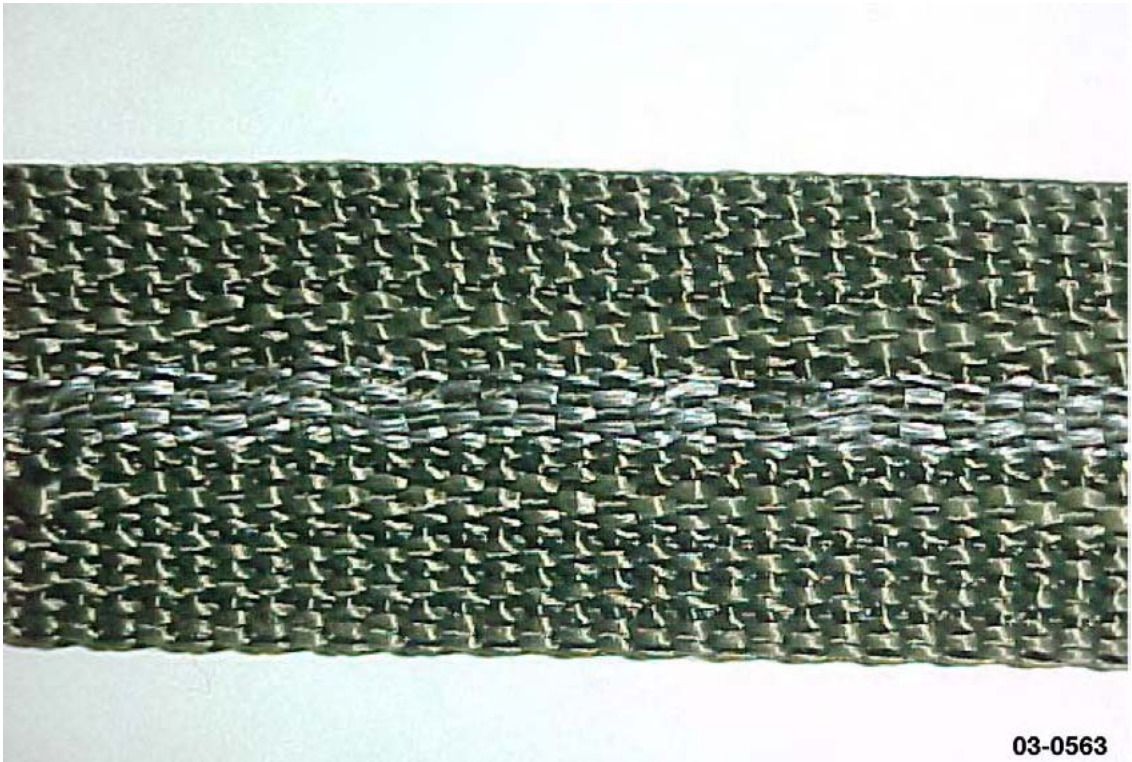


***Figure 8.	Second iteration of USB v1 cable showing improvement in dimensional stability of the wires and shielding***

Contech Research subcontracted the EMI shielding effectiveness testing to National Technical Systems (NTS) of Fullerton, CA. Foster-Miller obtained a non-disclosure agreement with National Technical Systems to design a testing protocol to establish the shielding effectiveness of the prototype flat USB cable. NTS has the capability to do USB shielding compliance testing, the one aspect of USB compliance testing that Contech Research does not have in-house. The USB shielding effectiveness specification is for the entire cable/connector assembly. However, Foster-Miller needed to have some information about shielding prior to connector design, and so the exact USB specs could not be used. Foster-Miller, together with NTS, designed a series of tests that gave useful absolute data on shielding effectiveness of the cable alone.

Contech Research performed USB Qualification testing in accordance with USB C7C spec 2.0, subgroup 6. The five tests in this subgroup including Capacitive Load, Cable Impedance, Propagation Delay, Propagation Delay Skew, and Attenuation. Shielding Effectiveness testing was performed in accordance with USB 2.0 and EIA 364 test procedure 66. Testing was performed on three different cable replicates, and an average value was calculated for each test. Shielding Effectiveness tests were only performed on two cable replicates. The cables provided for testing were all 5m in length. These cables were cut at Contech Research, and each test was performed on each cable at lengths of 5.0m, 4.0m, 3.0m, 2.5m, 2.0m, 1.0m, and 0.5m. Figure 9 shows a sample cable that was cut and fitted with end pieces for the appropriate testing. Table 5 summarizes the results of the first five tests.

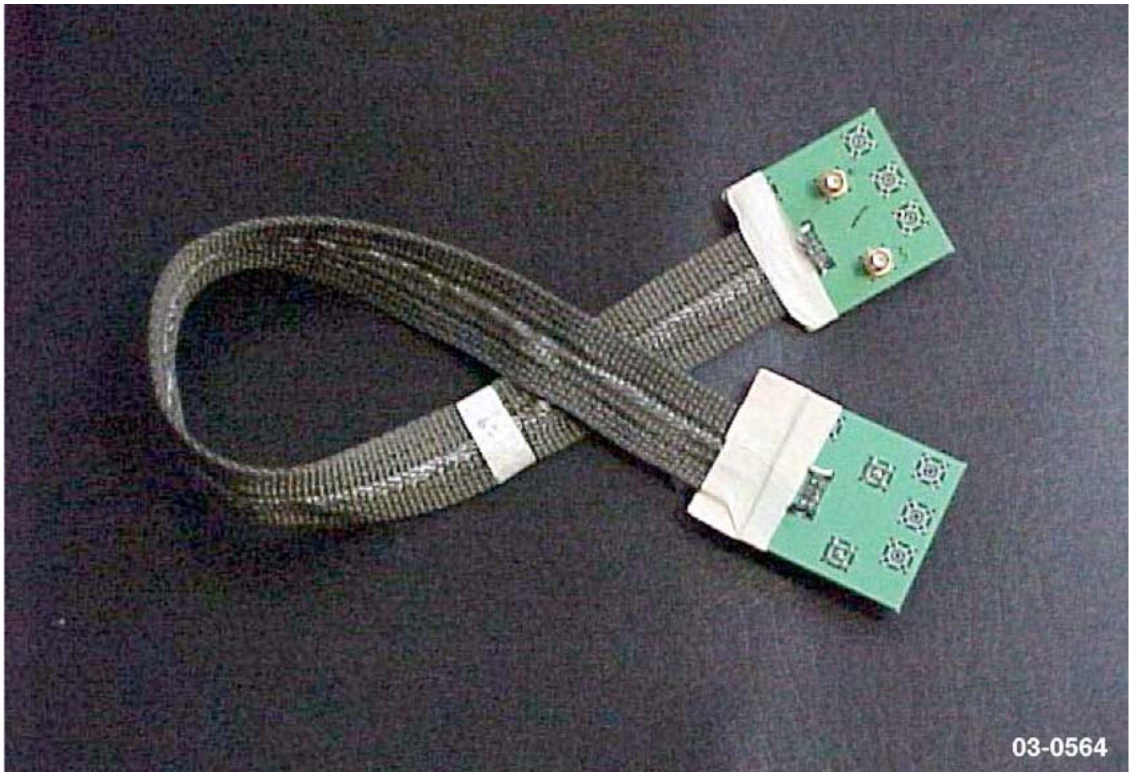


Figure 9. USB cable post-compliance testing

Table 5. Pass/fail status of USB cables

Cable Length	Capacitive Loading (low speed)	Cable Impedance (full speed)	Propagation Delay	Propagation Delay Skew	Attenuation (full speed)
5.0m	Pass	Pass	Pass	Pass	Fail
4.0m	Pass	Pass	Pass	Pass	Fail
3.0m	Fail	Pass	Pass	Pass	Pass
2.5m	Fail	Pass	Pass	Pass	Pass
2.0m	Fail	Pass	Pass	Pass	Pass
1.0m	Fail	Pass	Pass	Pass	Pass
0.5m	Fail	Pass	Pass	Pass	Pass

Initial Inspection

To assure that the test replicates met the workmanship standards normal for USB cables, and had not sustained any damage during shipment, all cables were inspected. Testing comprised of a visual exam under 10x magnification for damage, distortion, chipping, marking conformance and legibility. All cables showed no evidence of physical damage, the markings were legible and intact, and the contacts exhibited no cracks or peeled plating. All the replicates were then coded, identified, and mated. Mated cables remained with each other throughout the test sequences for which they were designated.

Capacitive Load

Capacitance is a measurement of how a cable design can store the electrical charge of the signal. It is based on two conductors, in this case the signal pair, and the medium between them. The capacitance can be changed by spreading the wires apart or adding more material between them. Capacitive load testing was performed to ensure that the distributed inter-wire capacitance was less than the lumped capacitance specified by the low-speed transmit driver. This test is only required for low-speed cables, and is performed on both sides of the cable. The specifications require that the capacitive load be between 200 and 450 pF. *Only the 5.0m and 4.0m cables satisfied this criterion*. The 3.0m cable has a capacitive load of 165.87 pF on one side, and 165.37 pF on the other. The smaller lengths of cable all have lower loads. *While the longer cable lengths did not pass, this test is only required for low-speed cables and therefore the cable receives a PASS rating at high speed.*

Cable Impedance

Impedance is a parameter that determines a cables ability to pass energy efficiently. When signals transfer from one piece of electronic equipment to another, especially at high frequencies, the cable must match the components that send and receive the signal. Cable impedance testing is required only for high-/full-speed cables, and was performed to ensure that the signal conductors have the proper impedance. Again, this test was performed on both sides of the cable. Cables that pass this test have impedances in the range of 76.5 to 103.4Ω. The lowest impedance measured in our cables was in one of the 0.5m cables at 86.1Ω. The highest impedance was in a 5.0m cable at 102.1Ω. Thus, all cables passed this test.

Propagation Delay

Propagation delay is the time required for a digital signal to travel from the input of a cable to the output. Propagation delay is important because it has a direct effect on the speed at which a digital system can operate. Propagation delay tests were performed to verify the end to end propagation of the cable. In accordance with EIA 364, test procedure 103, to pass the low-speed specs, the propagation delay must be no more than 5.2 ns/m. The 0.5m through 4m cables met this requirement. The 5.0m cable is at the threshold with an average speed of 26.03 ns, and a requirement of 26.0 ns.

Propagation Delay Skew

The propagation delay skew tests verify that the signal of both the D^+ and D^- lines arrive at the receiver at the same time. The standards require a differential of less than 100 ps. All cables easily passed this test.

Attenuation

Attenuation is a measure of signal loss in a cable. Attenuation tests are only required for high or full speed cables and are performed to ensure that adequate signal strength is presented to the

receiver to maintain low error rates. The test was performed on both sides of the cable. A summary of the attenuation data can be found in Table 6 along with the maximum acceptable cable loss at various frequencies. The italicized values indicate unacceptable attenuation losses. The data shows that the USB cables fail at long lengths. *For the purposes of outfitting the soldier, however, only short cable lengths will be required. The cables pass attenuation tests at lengths of 3.0m and shorter.*[1]

Table 6. Attenuation losses of USB cable

Frequency (MHz)	Maximum (dB)	Cables						
		0.5m	1.0m	2.0m	2.5m	3.0m	4.0m	5.0m
0.512	0.13	0.017	0.053	0.072	0.087	0.109	0.139	0.178
0.772	0.15	0.022	0.045	0.094	0.114	0.136	0.183	0.230
1.0	0.20	0.027	0.053	0.111	0.134	0.160	0.207	0.267
4.0	0.39	0.052	0.104	0.215	0.260	0.312	0.418	0.530
8.0	0.57	0.071	0.142	0.294	0.359	0.433	0.583	0.736
12.0	0.67	0.083	0.167	0.358	0.445	0.539	0.720	0.884
24.0	0.95	0.125	0.258	0.511	0.597	0.678	0.863	1.094
48.0	1.35	0.156	0.308	0.580	0.715	0.859	1.123	1.403
96.0	1.90	0.210	0.427	0.793	0.978	1.155	1.524	1.899
200	3.20	0.466	0.683	1.211	1.486	1.749	2.283	2.800
400	5.80	0.801	1.109	1.953	2.327	2.743	3.516	4.115

Shielding Effectiveness

Shielding effectiveness tests were performed to determine the electromagnetic emission profile and susceptibility of the cable. The minimum attenuation required to pass the test is 20 dB. Testing occurred at 13 frequencies between 30 MHz and 1 GHz. *All the USB cables clearly achieved the 20 dB mark at all frequencies, with the lowest being 35.9 dB (Appendix A).* In summary, the USB cable passed the high speed data requirements and was effectively qualified and ready for connectorization.

3.2.1.4.4 USB Version 2

Since the observed waviness of the USB v1 cable and the majority of its stiffness can be attributed to the Shielded Twisted Pair (STP) and the power pair, we decided to focus our efforts on redesigning these components to produce a more textile compatible cable. A batch of twisted pair had been produced using a low durometer Thermo-Plastic Elastomer (TPE) insulator rather than High Density Polyethylene (HDPE). This one change was found to markedly reduce the stiffness of the twisted pair. It was therefore decided to replace the HDPE insulation on both the STP and power pair wires with TPE.

[1]It should be noted here that in the report from Contech Research (Appendix A) the summary test results list that the cable passes signal attenuation at all lengths. Mr. George Olear, Director of Mechanical/Environmental Testing, was contacted about this inconsistency. He reported that the requirements of the USB attenuation specification are under dispute at this time. The required dB as a function of frequency does not follow the standard mathematical function for attenuation. Therefore, they have been given judgment by the standards committee to accept values within a certain tolerance level.

To further reduce the stiffness and improve the overall performance of the twisted signaling pair and power pair we decided to redesign the conductors themselves. The USB 2.0 standard specifies that the 28 AWG data wires and 22 AWG power wires be constructed of bundles of 36 AWG and 28 AWG copper filaments respectively. Foster-Miller instead constructed the 28 AWG data wires and 22 AWG power wires using bundles of 40 AWG silver plated copper filaments. While more expensive this one change significantly improved the flexibility and fatigue life of the conductors.

Together these changes produced twisted pair and power wires that were more flexible and more compatible with the weaving equipment than their predecessors. This resulted in a USB cable that in addition to being more flexible was uniformly flat and had far fewer kinks and less waviness than the USB v1 (Figure 10). Poke-through could still be observed in certain locations in the cable. These instances were rarer and less pronounced than in the earlier USB design. Changing the insulation also had the unanticipated but desirable effect of increasing the friction between the power pair and the textile. Slippage was reduced to the point that even using a pair of pliers it was extremely difficult to pull the conductors out of a relatively short length of cable. We anticipated that the changes made to the USB design would greatly reduce or eliminate the phenomenon of poke-through without the need to resort to a denser and hence stiffer weave. As will be discussed in subsection 3.2.2.1, wire "poke through" was still observed during hex abrasion tests but was less significant than in earlier tests conducted with USB v1 cables. We observed that slippage between the wires and textile was confined locally to the area of abrasion and as such would not be mitigated by connectorizing the cable ends. We also observed that once wires in the USB v2 design were exposed they did not stand up as well to abrasion as those in the earlier USB v1 design.

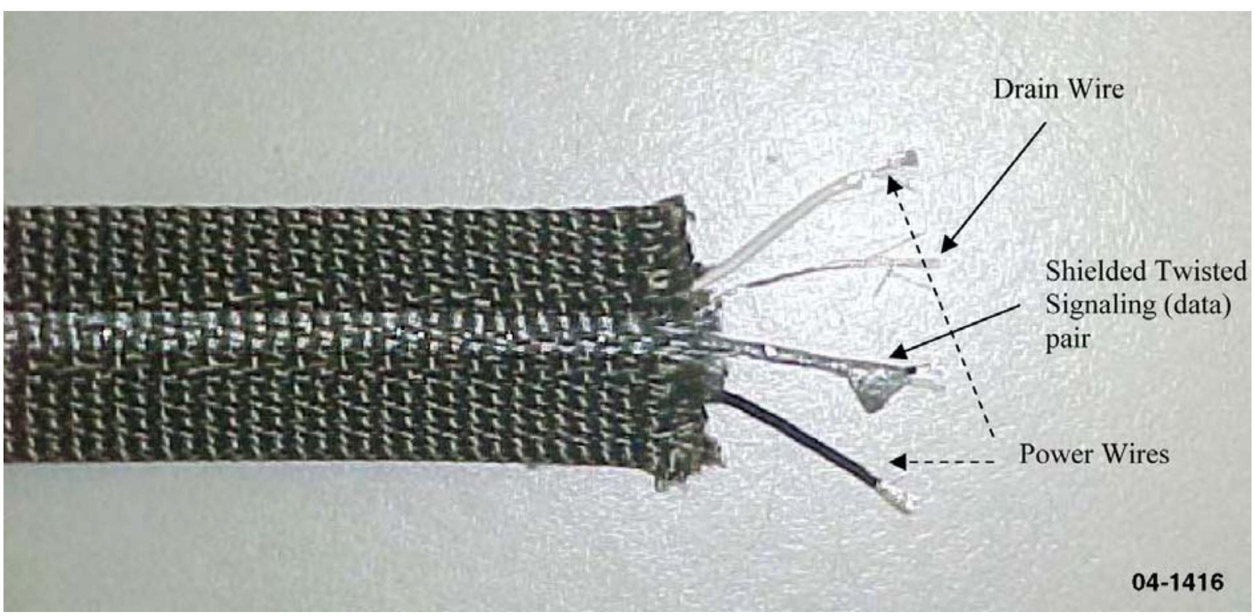


Figure 10. USB Version 2

Based on the success of these design changes a meeting was held with New England Wire to determine what other steps could be taken to improve conductor flexibility. It was found that NE Wire could furnish conductors made of an ultra-high flex life, cadmium based alloy in filament sizes as small as 50 AWG. Given the increase in flexibility observed when changing the conductor filaments from 28 to 40 AWG it is likely that this product will prove to be extremely textile compatible. NE Wire furnished us with samples of this product but it was found to be far too expensive for our purposes. Figure 11 shows the relationship between the cost per 1000 ft of 22 AWG power wire and 28 AWG shielded twisted pair and the filament gauge. Based on this information it was decided that it would not be cost effective to use copper wire filament smaller than 44 to 46 AWG.

5-Conductor Cable

To have a cable that was compatible with 5-conductor 0F Lemo connectors, Foster-Miller modified a cable run at Offray to produce approximately 35 yards of 3/4 in. wide, 5 conductor cable shown in Figure 12. This cable was identical to the USB v2 produced previously except that it is narrower and contains an additional power conductor.

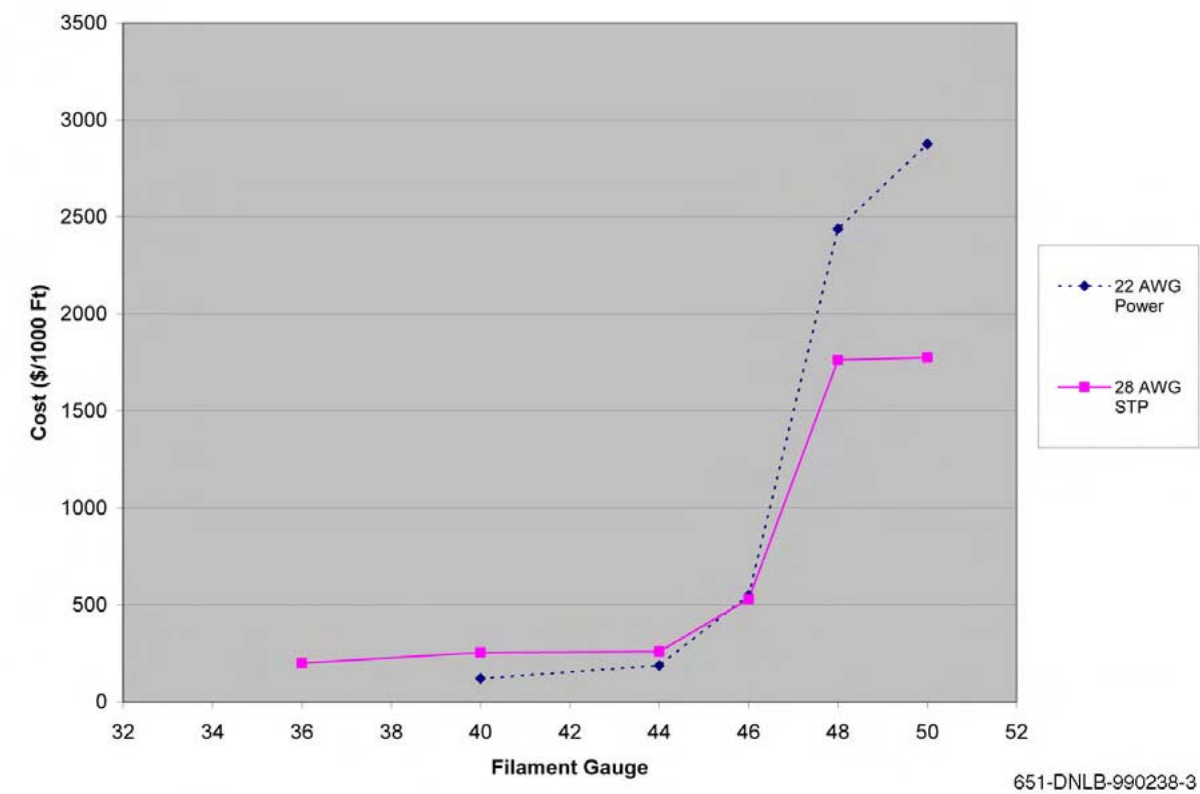


Figure 11. Unit cost of stranded wires as a function of filament gauge for 22 AWG power wire and 28 AWG shielded twisted pair (STP) (this work was funded jointly by DAAD16-99-C-1016 and DAAD16-02-C-0006)

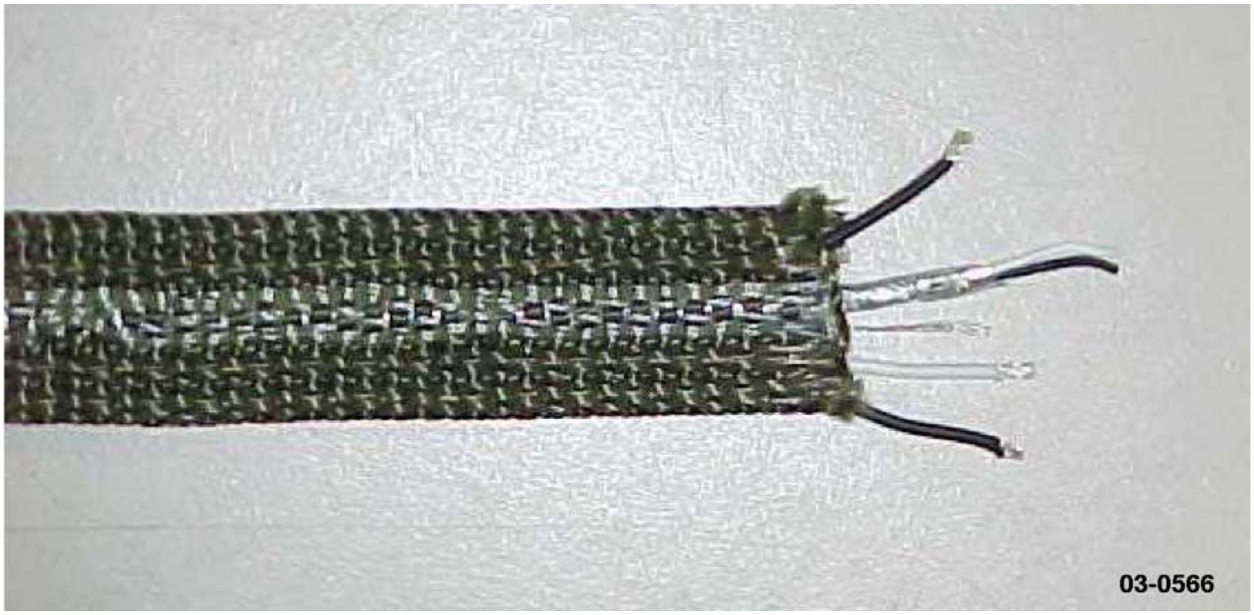


Figure 12. 5-conductor cable for demonstration with 5-conductor connectors

3.2.1.4.5 USB Version 3

Redesign of EMI Shielding

We believed that replacing the aluminum/Mylar® shielding used in the first two USB designs with a round hollow conductive braid could provide several advantages, including better shielding effectiveness, increased flexibility and extended flex life. To test this assumption a twisted pair was overbraided using Japanese technique known as "Kumihimo." The braiding technique and apparatus are shown in Figures 13 and 14, respectively.

The round, hollow braided shield created for this evaluation (Figure 15) consisted of sixteen conductive yarns; eight of DuPont™ XN0400E-018 shielding grade Aracon®, a nickel clad fiber, and eight of Bekaert's VN8/1x100/40Z/316L stainless steel yarn. Considering the fineness of the fibers used and the small diameter of the twisted wire pair, the sixteen strand, round, hollow braid was felt to provide the best coverage, flexibility and uniformity to the finished overbraided

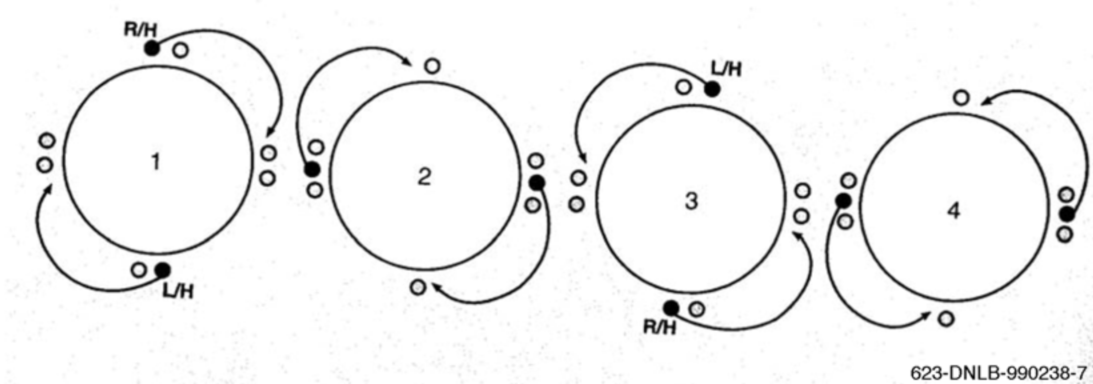


Figure 13. Kumihimo braiding process

Figure 14. Kumihimo braider setup

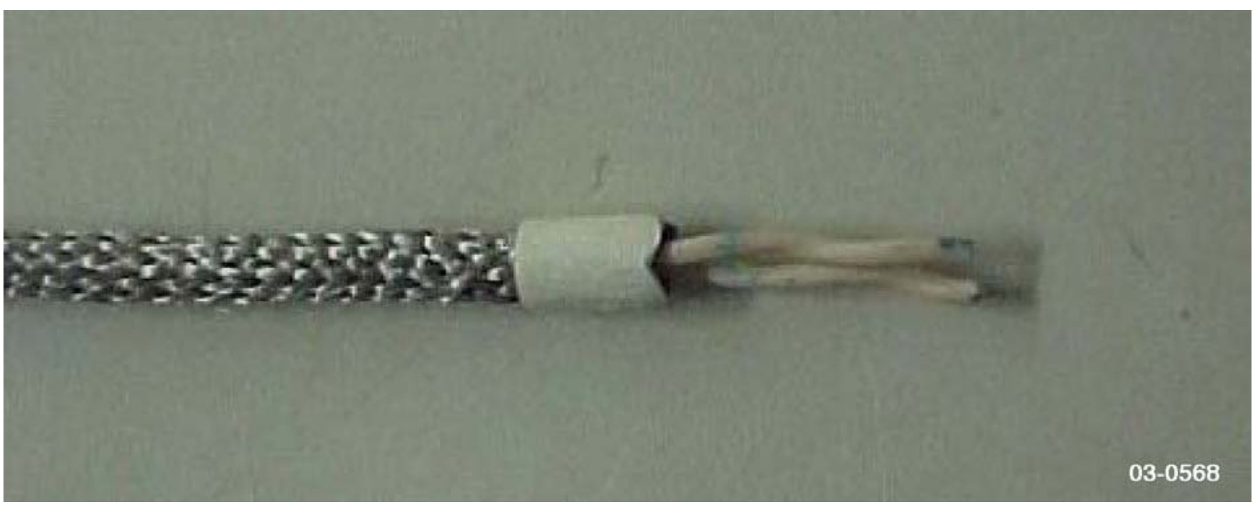


Figure 15. Twisted pair with Aracon®/stainless steel braided shielding

wire. The round braid is commonly used in the textile world, which makes it manufacturable with the use of standard braiding machines. The number of strands needed to achieve full coverage is dependent in part on the fiber thickness. In this case, sixteen strands were required to fully cover the wire; larger diameter fibers would reduce the number of strands needed. Once 6m of the shielded twisted pair (STP) was produced, ~5m were sent to Contech Research for Shielding Effectiveness evaluation and the remainder kept at Foster-Miller for demonstration purposes. Contech assessed the shielding effectiveness at lengths of 4.7m, 3.0m and 1.0m.

The results of this evaluation (Table 7) appear to indicate minor problems with the shielding effectiveness of the S.S./Aracon® hollow braid falling outside the USB 2.0 specification limit of –20 dbm at lower frequencies (50 to 70 MHz). Upon further investigation it was observed that these drops in shielding effectiveness only occurred at those signal wavelengths that were close to the physical length of the test specimen. Figure 16 shows how the frequency at which the specimens shielding effectiveness dips most noticeably increases as its length decreases. These end effects are easily avoidable and were due to the shielded twisted pair being terminated in a non-ideal manner resulting in reflected energy. At higher frequencies the effectiveness of the braided shielding can be seen to improve markedly (Figure 17). Given the overall shielding effectiveness results and how close the STP came to passing even at low frequencies it is reasonable to assume that were the STP properly terminated and tested it would easily exceed USB requirements.

Table 7. Shield effectiveness of Aracon®/stainless steel hollow braid shielding

Frequency (MHz)	Wavelength (m)	Shielding Eff (4.72m) (dbm)		Shielding Eff (3.0m) (dbm)		Shielding Eff (1.0m) (dbm)	
		Vertical	Horizontal	Vertical	Horizontal	Vertical	Horizontal
30	9.993	-20.4	-28.9	-27.1	-29.5	-30.4	-31.5
50	5.996	*-16.3*	*-17.7*	*-18.9*	*-19.8*	-28.9	-23.1
70	4.283	-27.3	-24.8	*-17.5*	*-18.6*	*-17*	-20
100	2.998	-25.1	-33.1	-20	-23.3	-27.9	-23.7
200	1.499	-46.5	-36.9	-27.2	-24.1	-31.7	-35.6
300	0.999	-37.3		-30.4		-36.1	
400	0.749	-42.1		-35		-53.2	
500	0.600	-43.8		-40		-42.9	
600	0.500	-49.1		-27.6		-42.7	
700	0.428	-33.1		-39.1		-55.6	
800	0.375	-42.4		-37.9		-31.9	
900	0.333	-35.3		-45.6		-45.5	
1000	0.300	-34.7		-31.7		-33.8	

Conductive Elements

To further improve upon the design of the USB v2 a series of changes were made to its construction. This final USB design replaced the TPE coated copper wires with a Tefzel® coated 400 denier XN0400F-040 conductor grade Aracon® yarn. Tefzel® is a fluoropolymer produced by Dupont™. The shielding for the new twisted pair was also redesigned based on the work discussed above. Due to the smaller diameter of the Aracon® yarns used in the USB v3 cable the braided shielding required only eight individual strands – four of DuPont™ XN0400E-018 shielding grade Aracon® and four of Bekaert's VN8/1x100/40Z/316L stainless steel yarn. The shielded twisted pair used in the USB v3 cable, and the earlier braided shielding trial are shown in Figure 18 on the bottom and top respectively. To further improve cable flexibility the width of the narrow woven was reduced from 1 in. to 3/4 in. A 6-yard sample run of the USB v3 was

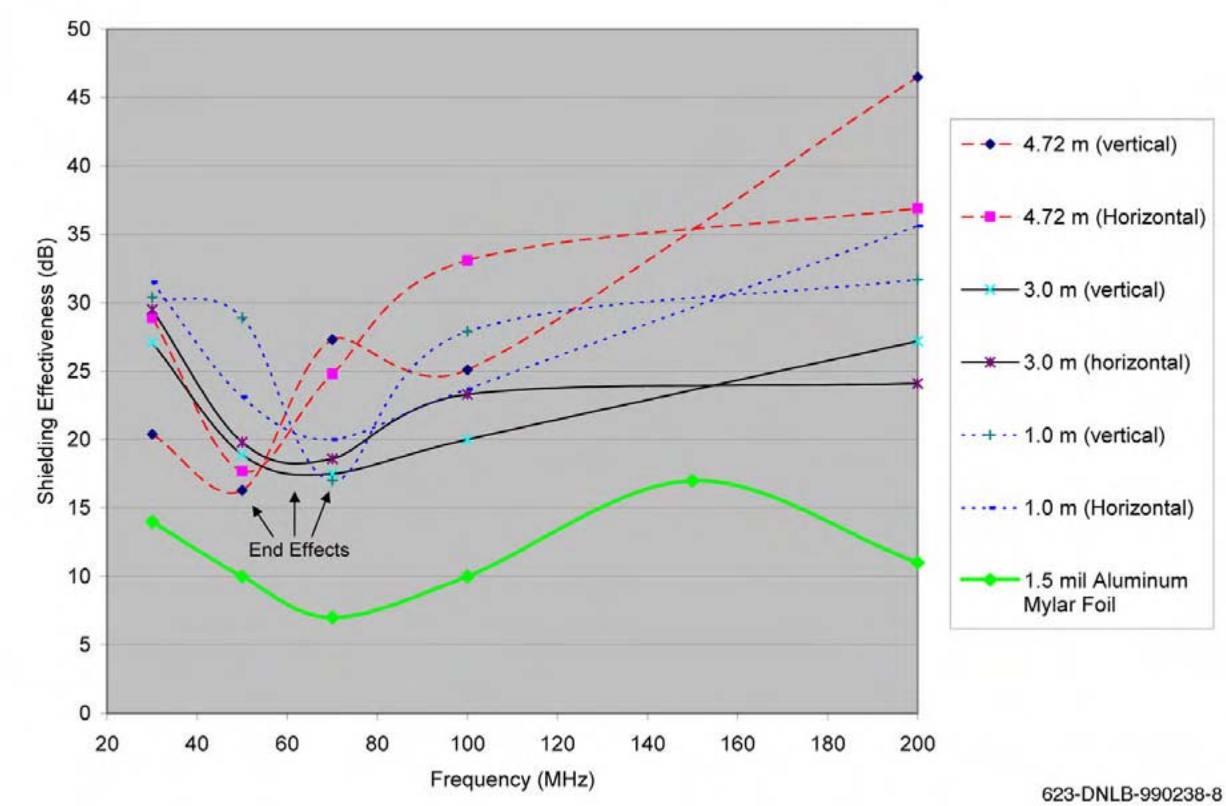


Figure 16. Low frequency shielding effectiveness of Aracon®/S.S. braid

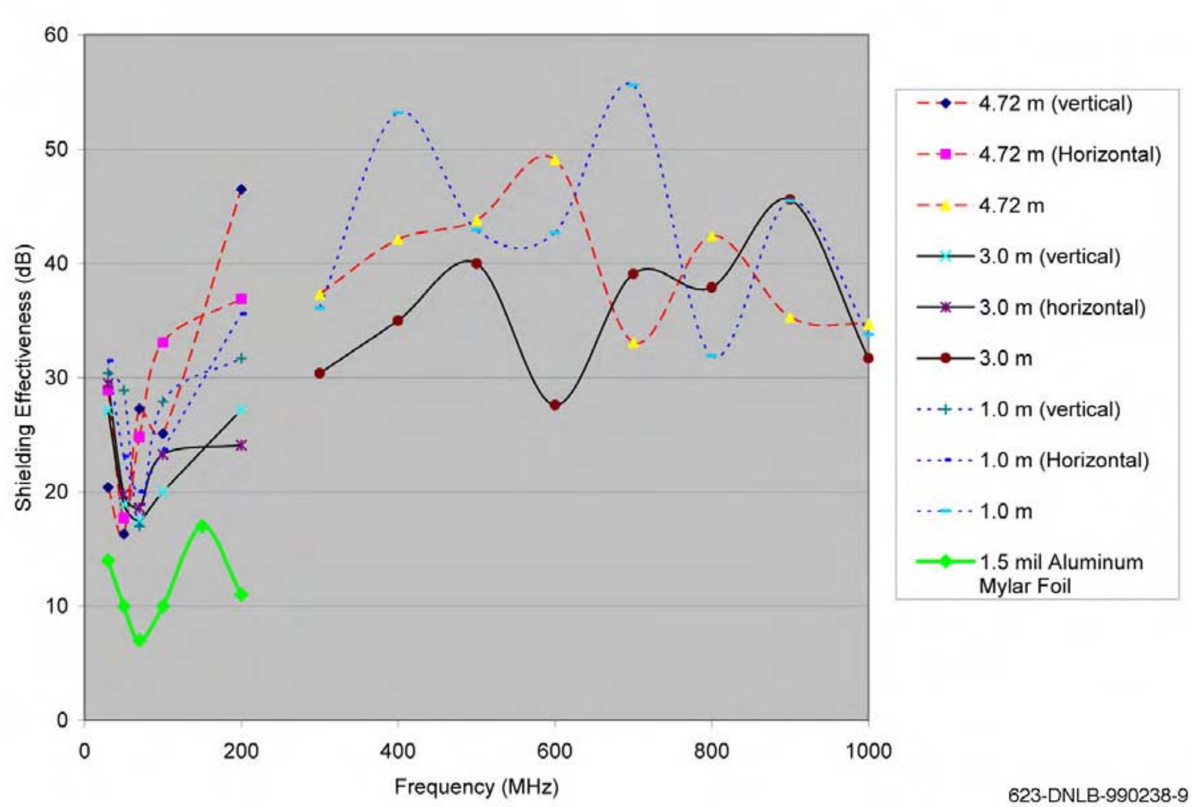


Figure 17. Low and high frequency shielding effectiveness of Aracon®/S.S. braid

Figure 18. ***Round, hollow braided shielding consisting of Aracon® and stainless steel. The top twisted pair is a TPE coated copper conductor while the bottom is a Tefzel® coated Aracon® conductor***

produced at Offray for evaluation purposes (Figure 19). It was observed that the USB v3 cable was the flattest of the three USB cable designs, with no observable kinks, waviness or "poke-through."

As will be discussed later in subsection 3.2.2.2, it was found that despite the improved flexibility of the textile structure and the Aracon® conductors the overall cable structure was slightly stiffer than the USB v2 cable. This was found to be due to the high stiffness of the

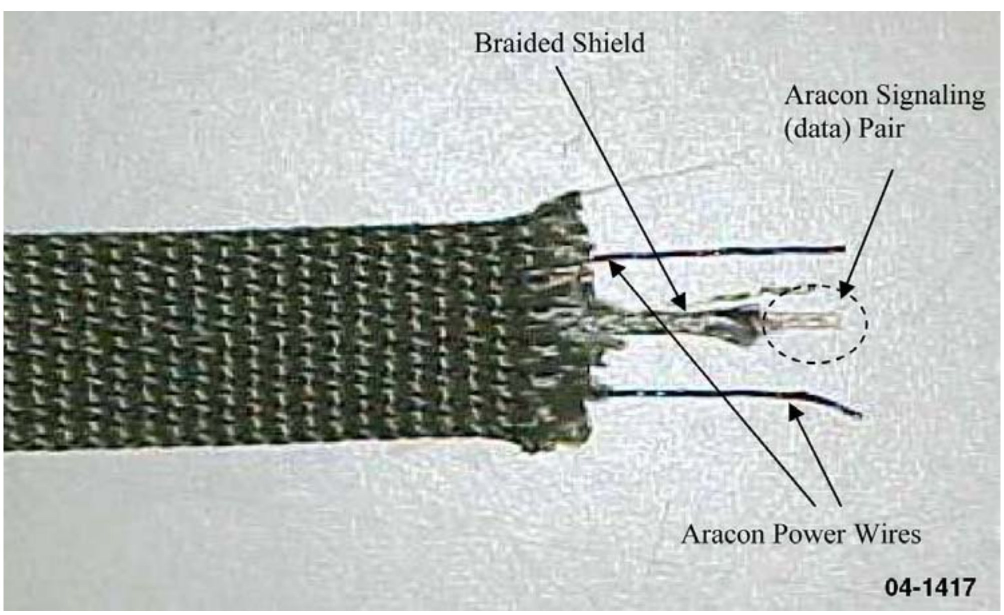


Figure 19. USB v3 cable using Tefzel® coated Aracon® conductors

Tefzel® used to insulate the Aracon®. Work is currently underway on Contract DAAD16-02-C-0006 to find Aracon® compatible insulation materials that are more flexible than the Tefzel® used here.

3.2.1.5 Implementation of IEEE 1394 Specifications

Both the IEEE 1394-1995 standard and the proposed IEEE 1395-2000 standard for "Firewire" were examined to determine the proper cable construction. There are four different ways that the Firewire can be made:

- All copper wires (i.e., both power and data).
- Plastic Optical Fiber (POF) for data transfer.
- Hard Core Polymer optical Fiber (HCPF) for data transfer.
- Glass Optical Fibers for data transfer.

Figure 20 shows the configuration of the all copper Firewire cable. The cable has many structural similarities to the USB, requiring foil wrapped twisted pairs. Upon examination, we determined that a narrow woven replicating this structure would be more bulky than the USB narrow woven; and, we would not be developing new technology information from its manufacture. These two points, combined with the fact that the optical standard appeared to have more Army interests, led us to first pursue the optical standard with the intention of returning to the all-copper standard if funds permitted.

Foster-Miller consulted Boston Optical Fibers (BOF), a company specializing in the production of plastic optical fiber (POF), to determine the feasibility of using fiber optics for data transmission. BOF is the U.S. manufacturer of plastic optical fibers and was the supplier of the Phase I fiber used in the demonstration webbing. BOF had several Polymethylmethacrylate (PMMA) core based POFs with fluorinated cladding on the market and a new generation of all fluorinated core/cladding fibers in development. Primarily, their fibers are 1 mm in diameter, as this diameter highlights the main benefits of plastic fiber over silica based fiber; 2 mm, 0.5 mm fiber and 250µ fibers are also available.

BOF informed us that a plastic optical Firewire specification was very close to being released, and that such a standard will definitely exist. Boston Optical supplied Foster-Miller with advanced information on what would be contained in such a spec and provided us with data on the physical properties of the plastic optical fiber that they produce. Several other important points related to our IEEE 1394 development work were discussed:

- PMMA core fibers have a T_g at 80 to 85°C which allows them to be cut/melted in the field for quick addition of connectors. For our application, this temperature limitation may be a drawback. The 250µ optical fiber used during Phase I had to be made with a Kevlar® layer and then an external extruded jacket. The insulative Kevlar® protected the optical fiber from melting during the jacket extrusion. Fibers with diameters at or above 0.5 mm can be jacketed without protection. The new fibers under development will have glass transition temperatures above 100°C.

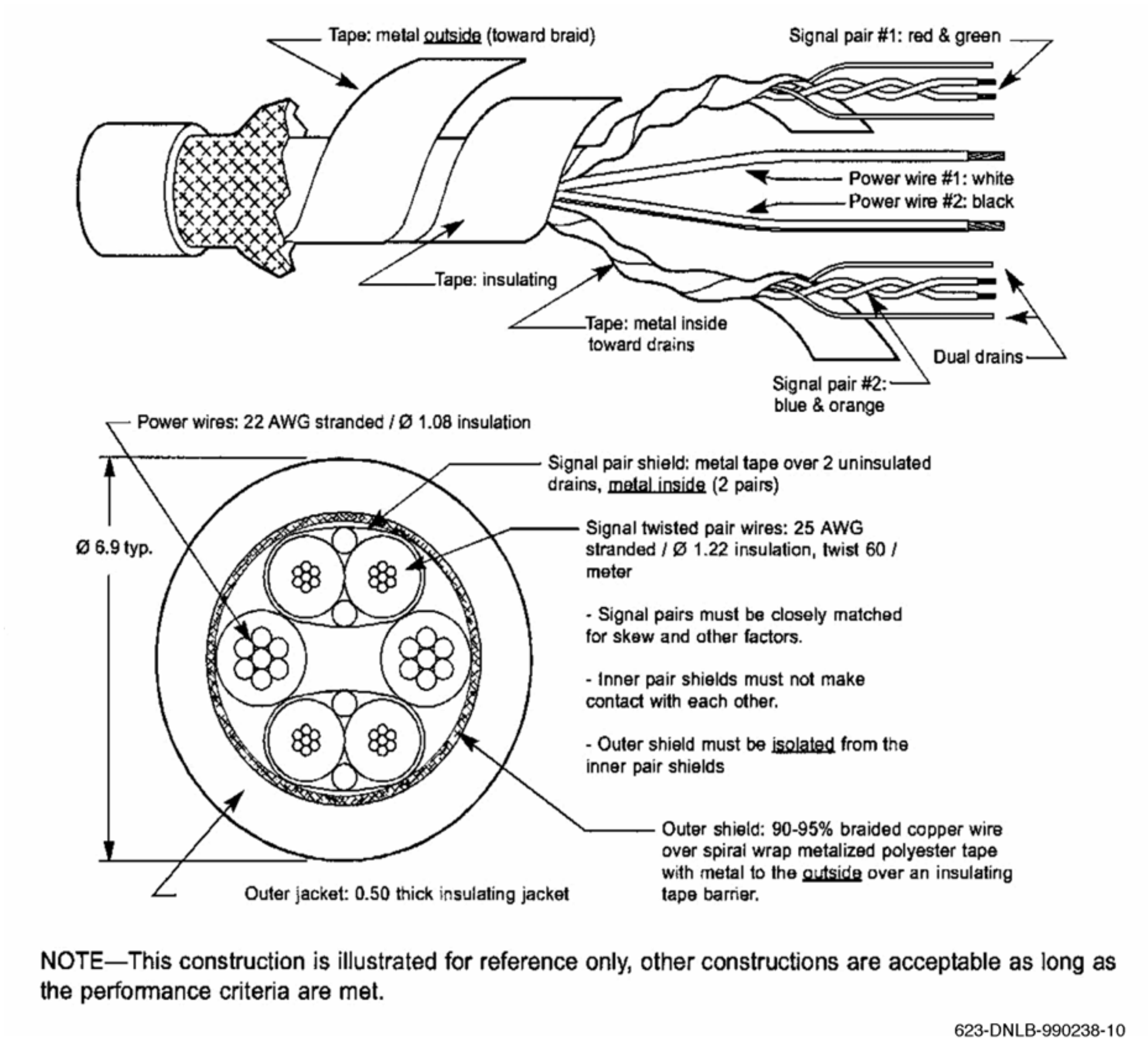


Figure 20. IEEE 1394 (Firewire) standard cable construction using all copper conductors. All units are in mm

- Plastic optical fibers have the same performance as silica based optical fibers when used over short distances. The characteristic length scales of the body fall into this range.

- Most POF connectors are toslink-based. Toslink is a connector format for fiber optic digital cables. These connector types rely on the ends of the fibers to come in close-to-actual contact to transmit the optical data and are limited to about 12 Mbit/sec data rates. This type of simple, inexpensive connector is possible because of the large fiber diameter (1 mm). The cores overlap within the tolerances of the injection molded connector parts, allowing data transmission.

Foster-Miller's basic textile Firewire design included a pair of copper wires for power transfer, and a pair of plastic optical fibers for data transfer. Shielding requirements were minimal, so no fiber shielding was required. A braided textile structure was used to compliment

the weaving work being done simultaneously on the USB cable. The braid configuration we used is shown schematically in Figure 21. The schematic shows the axial placements and not the bias fibers, which were all nylon. The flat braided tape consisted of 11 axials and 27 bias. The bias fibers were at a 45 deg angle to the axials.

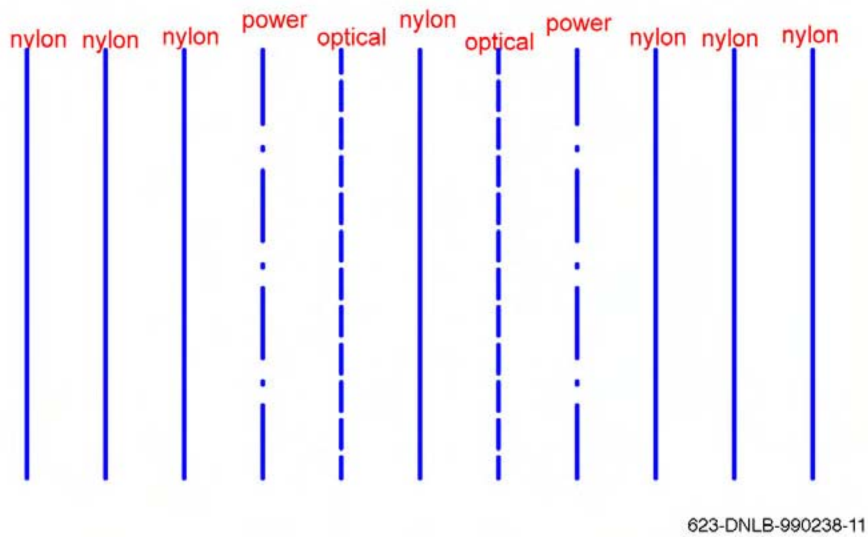


Figure 21. Schematic showing axial positions of FireWire braid design

All of the bias fibers were nylon (1260 denier), and two of the axials were optical fibers, two were 20 AWG power wires, and the remaining seven were nylon (Figure 22). Figure 23 shows that like the narrow woven USB, the braided Firewire cable had significant problems with kinks and waviness due to the stiffness of the copper wires. While this issue could be corrected, other issues were encountered that could not be so easily dealt with. As will be discussed in subsection 3.2.2.1, abrasion testing revealed that the braided nylon webbing used here could not withstand

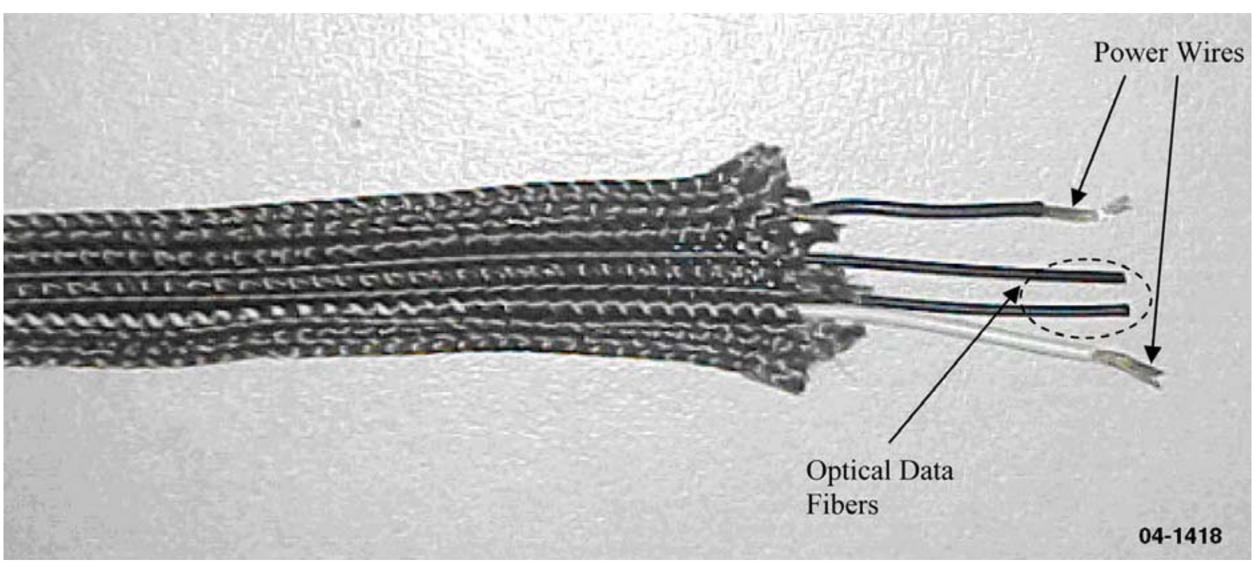


Figure 22. Electro-optic Firewire cable elements

Figure 23. Braided nylon electro-optic Firewire cable

much abuse. It was also discovered, as discussed in subsection 3.3, that duplex plastic optical connector inserts were not commercially available. Due to these concerns a decision was made to not pursue the Firewire cable design any further.

3.2.1.6 Skin Irritation Problem

During the spring of 2002 Plastics One reported that their technicians were experiencing problems with skin and nose irritations while handling samples of Foster-Miller/Offray narrow woven cables and antennas. As a result they declined to connectorize further cables until the source of these problems had been identified and corrective measures proposed. Since this issue caused delays in multiple Army programs (DAAD16-02-P-0042, DAAD16-02-C-0006 and DAAD16-99-C-1016) the cost of investigating it was spread among all affected programs. The results of this investigation were presented in the status reports for all affected programs. The report from Offray indicated that:

- USB webbing caused skin irritation during cutting and occasional bloody mucous discharge from the nose of certain individuals.
- Antenna webbing caused prickly-heat type reaction to hands and face.
- No problems were reported with the tinsel wire power bus used on the Heat Blanket.

Common components of these items are the nylon fiber. The USB webbing also contains stainless steel fibers while the antenna bus contains tinsel wire. After a quick examination of the complaints, the following potential causes of the irritations were compiled:

- Short chopped stainless steel fibers getting into skin or nose.
- Short chopped nylon fibers getting into skin or nose.
- Chemical residue on nylon from manufacturing.
- Chemical residue on tinsel wire from manufacturing.
- Chemical residue on narrow woven from manufacturing.

The following investigations were made to determine probable cause:

Lubricants/Spin Oils

- Offray reported that they did not use any processing aids such as lubricants on either the USB or antenna narrow wovens. Neither do they scour their product before shipment.

- Offray verified that the nylon used in the two products were from different batches.

- We confirmed with Dupont™ that the nylon could contain mineral oils used as a spin lubricant.

Stainless Steel

- Offray verified that significant fibrillation occurs of the stainless steel during the weaving process. Technicians who clean the looms have experienced skin irritation from short pieces of stainless steel.

- Bekaert did not report any skin irritation danger from the stainless steel product.

- Malden Mills, the largest user of stainless steel yarn, did report problems with skin irritation. Their solution was to coat the stainless steel yarn before knitting to reduce fiber breakage.

Tinsel Wire

- The particular tinsel wire used is run through a hot caustic cleaning bath (Sodium Hydroxide) and then a neutralizing water rinse during manufacture.

- Other tinsel wires in the same plant (Montgomery Wire) use a nitric acid plating process.

Nylon

- The denier of the fibers used is relatively high. Short chopped fibers would be stiff and could cause skin irritation.

Acidic or Basic Contaminants

A pH test was performed on samples of a narrow woven textile antenna developed under Army contracts DAAD16-99-C-1047 and DAAB07-01-C-L719. One test sample was cut from a batch of samples returned to us by Plastics One. The other sample was cut from a bolt of material that we had in-house. The nylon from these two specimens was known to come from different batches.

First, test samples weighing approximately around 5g each were cut in 2 in. lengths. The pieces were set aside while the starting pH of the water was tested. Approximately 10g of deionized water were added to two small glass beakers. This was the smallest amount of water able to sufficiently submerse the antenna material. A small amount of water made it easier to detect the presence of smaller concentration of contaminants. The starting pH of the water was tested using litmus paper. The pH of the deionized water was found to be 7 (neutral).

Next, the antenna pieces were added to the beakers. They were carefully placed on the bottom so that the entire piece was submerged in the water. The samples were left to sit for 30 min to permit any acidic and/or basic contaminants to transfer to the water. After the 30 min period, the final pH of the water was tested. The antenna samples were removed and the remaining water tested with litmus paper. The final pH readings from both antenna samples remained neutral with a reading of 7 on the pH scale. Therefore, it was found that there was no acidic or basic presence on the antenna pieces.

Diffuse Infrared Spectroscopy

Three sets of infrared spectra were collected:

1. Clean Braided Tinsel and Clean Braided Nylon.

2. "Contaminated" Tinsel and Nylon (Figure 24).

3. In house Tinsel and Nylon (from the same batch as the "contaminated" samples) (Figure 25).

Infrared spectra were collected on a Bomen MB155 FTIR Spectrometer with an MCT detector, a wave number resolution of 8 cm^{-1} and a scan rate of 256 scans. A DRIFT infrared fiber optic accessory was used to collect the diffuse reflectance spectra. Spectra were collected of the contaminated sample, as well as the contaminated nylon and the contaminated tinsel separately. The clean nylon and tinsel were available to use for comparative analysis.

The strong IR absorbing characteristics of the nylon made the analysis quite difficult. Variations in the peaks were hard to distinguish from the nylon backbone located at 1700 to 1000 cm^{-1}. Overall the spectra were non-conclusive. Slight differences at 1640 cm^{-1} and 1533 cm^{-1} (Figures 24 and 25) were initially attributed to nitric acid residue. Later discussion with the manufacturer of the tinsel wire negated this conclusion. Other peaks were difficult to

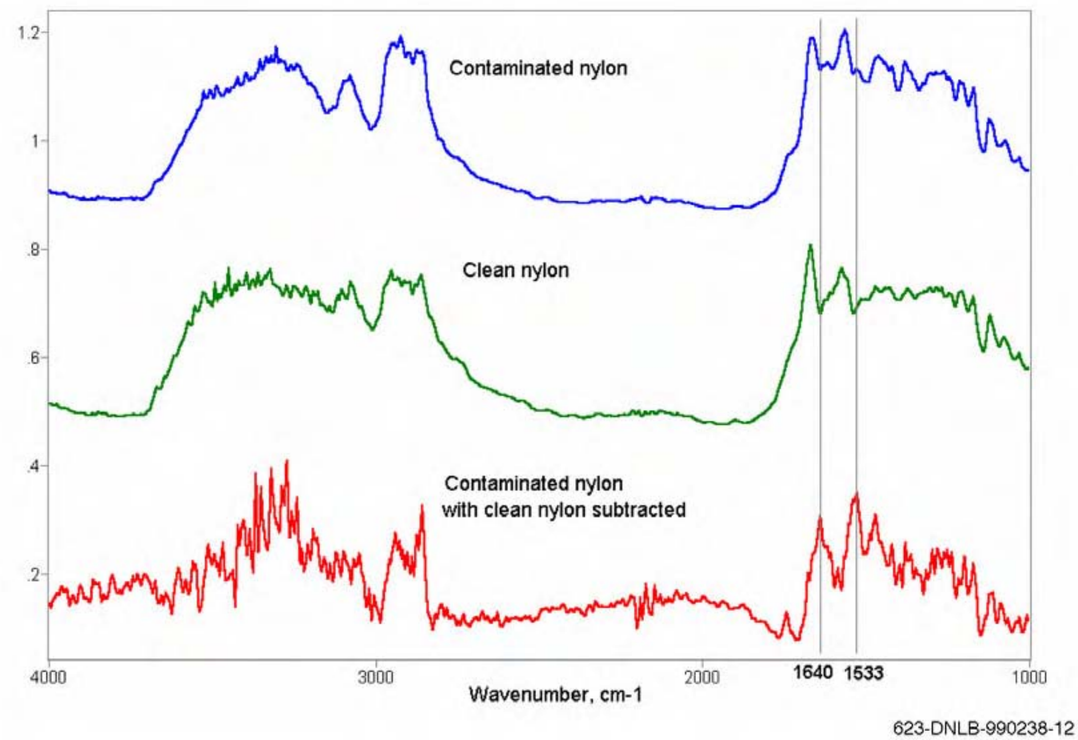


Figure 24. Spectral analysis L-R

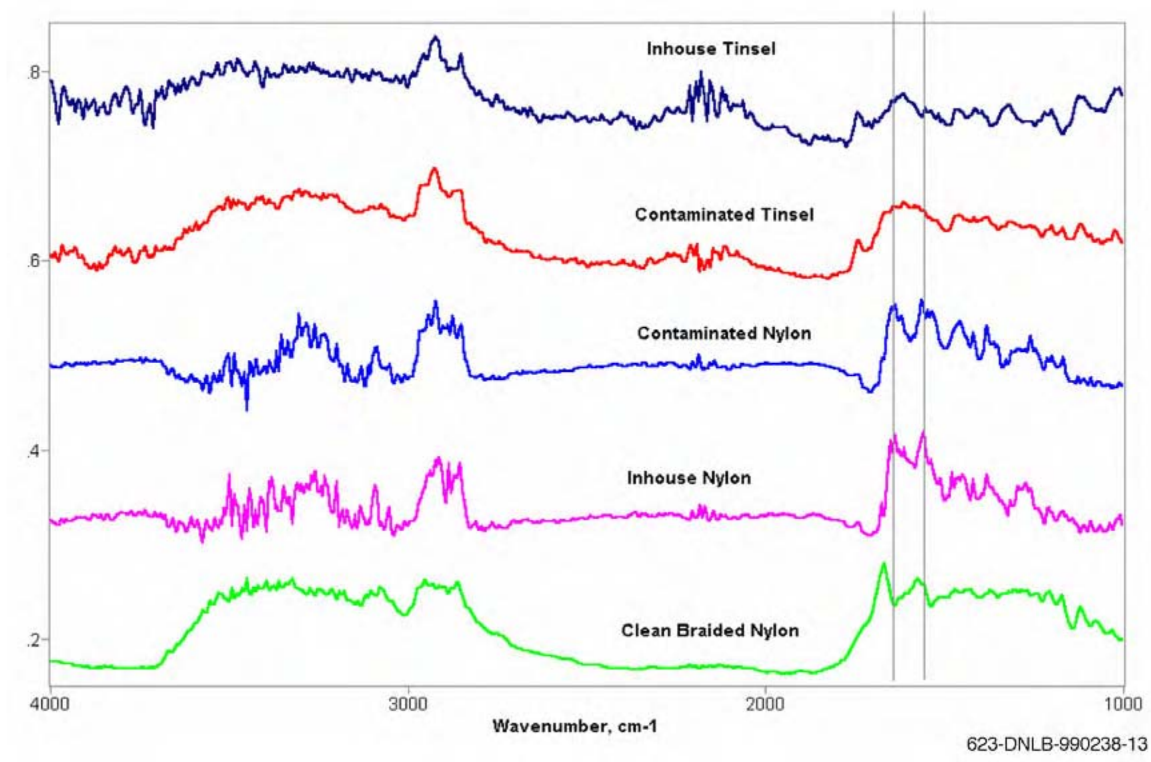


Figure 25. Spectral analysis L-R

assign to any unusually high concentration of oils (CH3 groups) or O-H bonds (water or sodium hydroxide).

The broad absorbency from about 3600 to 3200 cm^{-1} is characteristic of O-H bonds, while the peaks from 3000 to 2800 cm^{-1} are characteristic of hydrocarbons (CH_3 stretches).

The noise that is visible in some of the spectra at about 2200 cm^{-1} is due to a strong absorbing band in the fiber optic cables. This absorption allows very little light through at those wavelengths and therefore causes increased noise in this region.

Conclusions and Remedial Actions

We determined that the irritations were most likely due to the presence of short chopped stainless steel and/or nylon fibers that were generated at Plastics One during trimming or at Foster-Miller and remained on the surface of the webbing. Short fibers can also become airborne and get into the respiratory system depending on the local airflow.

To reduce this effect in future narrow wovens, Foster-Miller and Offray will change the denier of the individual nylon filaments if MIL-SPEC allows for a particular webbing to reduce the potential for skin irritation from short coarse fibers. In addition, the remedial coating procedure taken by Malden Mills to protect the stainless steel yarn will be used in future weavings to limit fiber breakage. We also recommended that when handling the narrow wovens for trimming or post-trimming to length, all personnel wear the following safety equipment:

- Gloves.
- Safety glasses.
- Lab coats.

During any trimming operations, either a dust mask or a suction airflow should be used at the station to avoid introduction of the fibers into the respiratory system.

3.2.2 Cable Testing

Two different bus standards were considered for use in the design of a communication system to be incorporated into the BDU. The USB 2.0 standard allows for transmission over twisted copper pairs at data rates of 1.5, 12 and 480 Mb/s. The 1394b standard allows transmission using a variety of media including Shielded Twisted Pairs (STP), Multi Mode glass optical Fiber (MMF), and Plastic Optical Fiber (POF) at data rates ranging from 100 to 1600 Mb/s depending on the media chosen. While full compliance with one of these specs may be useful at a later date and time it is currently not required. Since the connector design evolved in parallel with the cable design, testing focused only on the narrow woven cable itself. Furthermore, those issues which do directly effect the connector such as humidity and salt spray were pointless to investigate as neither the USB nor the IEEE 1394 make provisions for environmentally sealed connectors.

Given the demanding nature of the environment in which the Battle Dress Uniform must operate the textile bus must be extremely rugged and able to operate in a wide range of adverse conditions. Since the cable housing is a woven textile we must consider testing issues that are relevant not only to cables and textiles but to the integration of the two as well.

3.2.2.1 Mechanical Abrasion and Wear

Throughout its life cycle the soldier uniform will be subject to considerable abrasion by a variety of surfaces. To assess the cables' abrasion resistance, sample cable lengths were evaluated using a modified version of the ASTM D6770 standard, an abrasion test for textile webbing. This testing was carried out at Offray. The webbing abrasion test setup consists of a power driven oscillating drum as shown in Figure 26. One end of the specimen is attached to the drum while the other end passed over a 0.25 in. hexagonal steel rod. According to the standard, the steel rod should have a cold drawn finish and be free of any nicks, burrs or scales. Given that the cables breaking strength is between 1000 and 2000 lb a weight of 4 lb is called for by the test method. It was found, however, that this was insufficient to keep the cable in contact with the drum throughout the test so the next heaviest weight, 5.2 lb was used instead. The drum is oscillated such that the specimen is given a 12 in. traverse over the rod at a rate of 60 strokes per minute.

Initial tests exposed lengths of USB v1 and Fire Wire to 1000 cycles. The effect of 1000 cycles on the samples of USB v1 and Fire Wire can be seen in Figures 27 and 28, respectively.

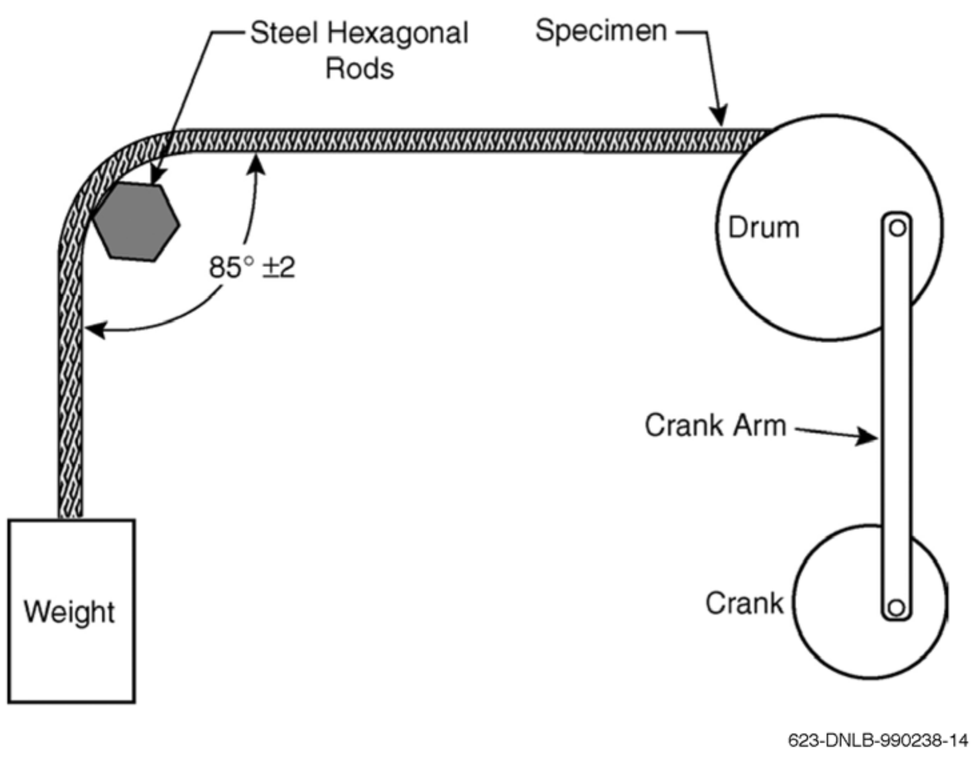


Figure 26. Abrasion over hex bar

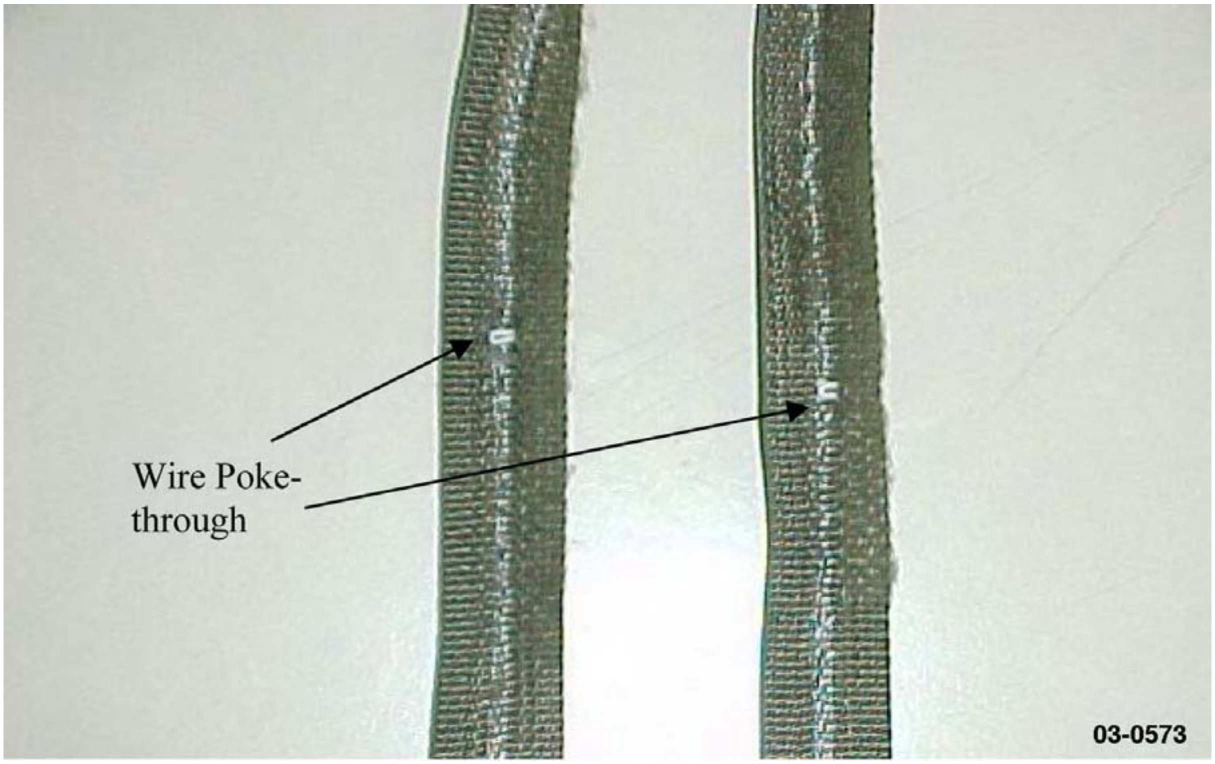


Figure 27. Effect of 1000 cycles of hex-abrasion testing on USB cable

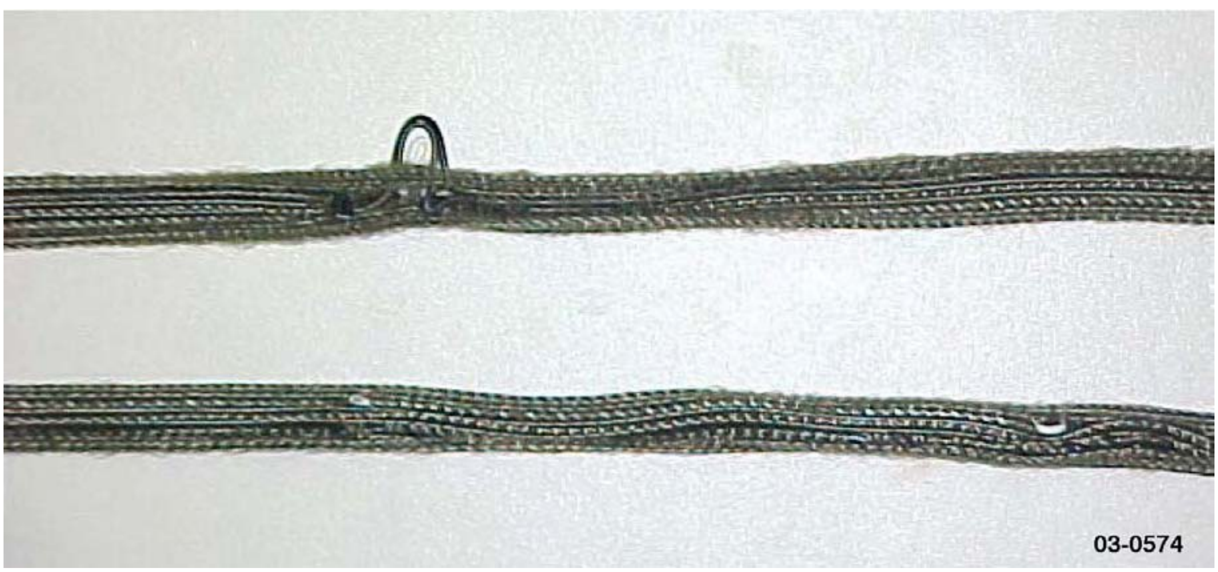


Figure 28. Effect of 1000 cycles of hex-abrasion testing on Fire Wire cable

Visual inspection of the samples revealed that the primary effect was to break and fray some of the nylon fibers of the webbing (Figure 29). It was also observed that the problem of wire poke through was aggravated by continued abrasion testing.

Figure 29. Close-up of effect of 1000 cycles of hex-abrasion testing on USB v1 cable

After testing, the USB v1 sample was sent to Contech Research for Group 6 signal integrity testing. The Fire Wire (FW) samples could not be tested, as Contech Research does not have the means to evaluate data transfer over plastic optical fibers. A summary of the test results is shown in Table 8. With the exception of characteristic impedance the abraded cables passed all test requirements. The results of the characteristic impedance tests shown in Table 9 indicate that these values were only slightly outside of the desired range. The complete test report can be found in Appendix A.

Table 8. Signal integrity data summary

Examination	No Damage	Pass
Characteristic Impedance	76.5 to 103.5 mΩ	High
Attenuation	3.2 dB and 5.8 dB maximum between 200 and 400 MHz	Pass
Propagation Delay	5.2 nS/m maximum	Pass
Propagation Delay Skew	100 ps maximum	Pass
Capacitive Load	200 to 400 pF	Pass

Table 9. Characteristic impedance results (milliohms)

"A" Connector				"B" Connector			
Sample ID	Minimum	Maximum	Average	Sample ID	Minimum	Maximum	Average
6-1	89.4	106.0	97.7	6-1	89.4	106.6	98.0
6-2	89.6	105.4	97.5	6-2	89.0	104.8	96.9

Based on these results we decided to test both the USB v1 and FW cables at 2000 and 4000 cycles. Before testing, the conductors in each cable were straightened using a pair of pliers so that any conductor "poke through" and waviness could be eliminated, resulting in a more uniform wear pattern. These tests were closely observed to determine at what point the wires began to poke through the textile. These tests revealed that after approximately 450 cycles the power pair of the USB v1 cable began to poke through the nylon webbing in places. As mentioned earlier, by 1000 cycles visual inspection of the samples revealed a slight increase in the poke through of the power pairs and some fraying of the nylon fibers. The effect of 2k and 4k cycles on samples of the USB v1 cable can be seen in Figure 30 and Figure 31, respectively. It is evident from these pictures that as the number of abrasion cycles increases the problem of the power pair poking through becomes increasingly worse. By 4k cycles, the twisted pair had managed to poke through the nylon and its shielding entirely. Damage to insulation the wire insulation was also observed.

A similar trend was observed for the FW samples tested to 2000 and 4000 cycles as shown in Figures 32 and 33. Visual inspection alone was enough to assess the ability of these cables to survive extended wear. After 1k cycles, we are already able to see significant poke through of the power pair and POF on the side opposite the hex bar. On the side rubbing against the hex bar we observed some fraying of the nylon braid and wear in places of the power pair's electrical insulation. At 2k cycles, the poke through has become worse and numerous sections of the power pair have been rubbed completely bare of insulation. By 4k cycles, the cable is a mass of frayed nylon with both the power pairs and POF worn completely through in several places. It is

Figure 30. Effect of 2000 cycles of hex-abrasion testing USB v1 cable

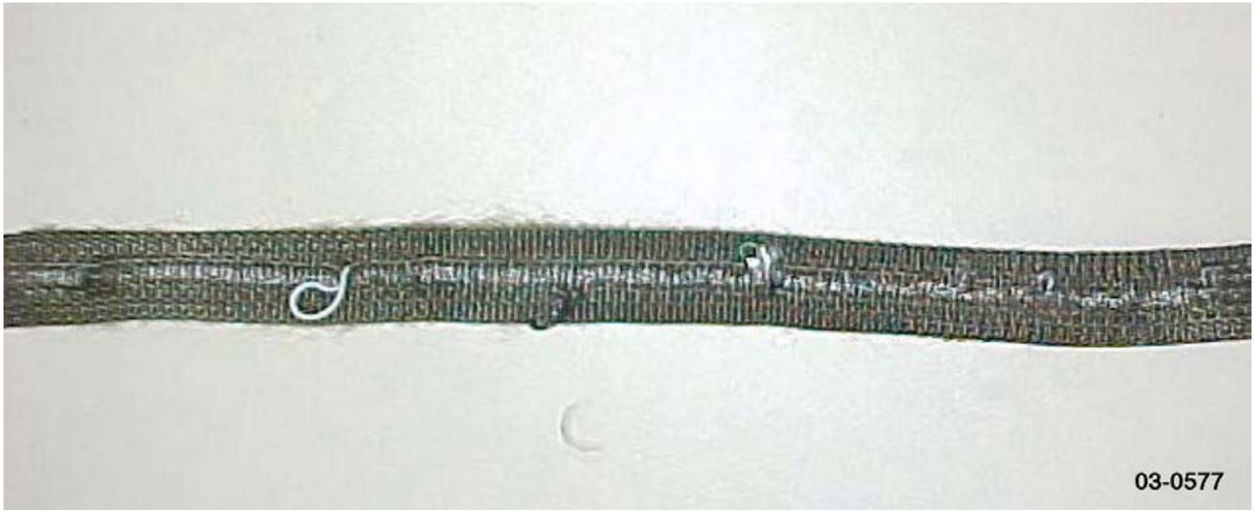


Figure 31. Effect of 4000 cycles of hex-abrasion testing USB v1 cable

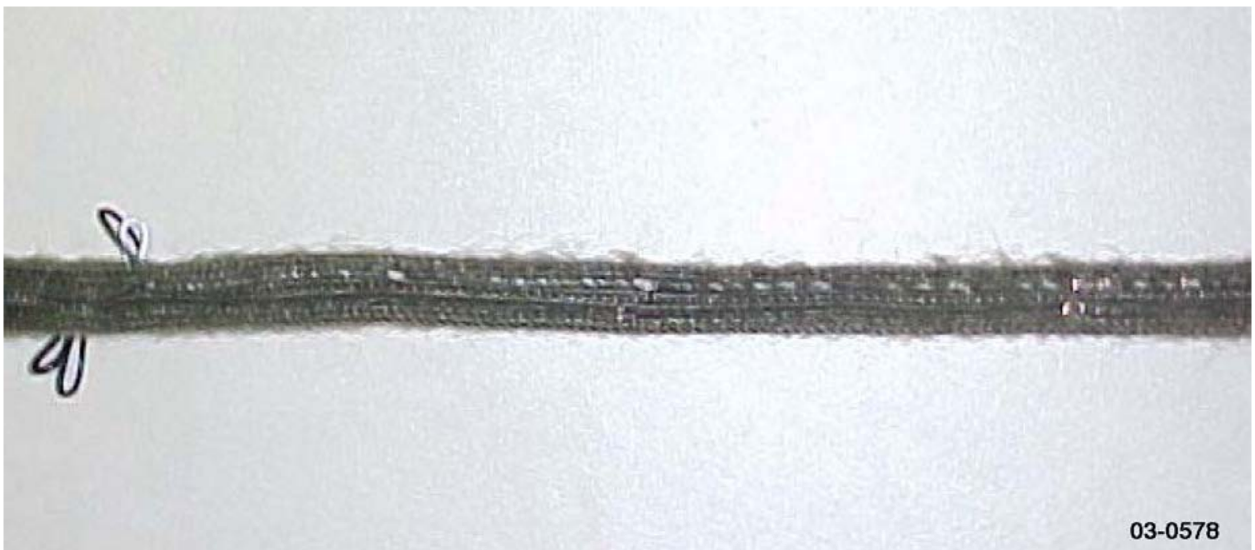


Figure 32. Effect of 2000 cycles of hex-abrasion testing on Fire Wire cable

obvious from these results that the current Firewire design could not withstand more than 1000 cycles before suffering electrical failure. Based on these observations, we determined that flat braids are not useful for rugged data cables and were not worth pursuing further in this Phase II effort.

"Poke Through"

Three factors have been identified as contributing to the observed "poke-through" phenomenon in the USB and FW cables:

- Wire stiffness.

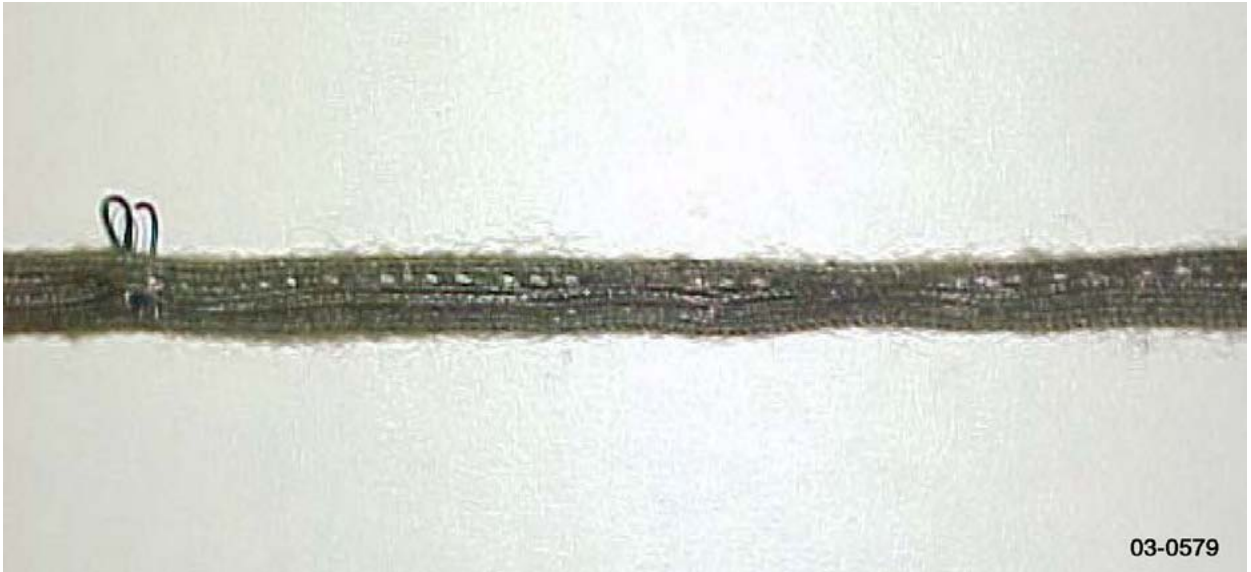


Figure 33. Effect of 4000 cycles of hex-abrasion testing on Fire Wire cable

- Tightness of weave/braid.
- Slippage between wires and textile.

Wire stiffness contributes to poke-through in two ways. First, it makes the wire difficult to incorporate into the weaving process. The result is typically a wavy or kinked conductor, which tends to deform the cable. Even without being subjected to abrasion testing these kinks exert pressure on the textile. Secondly the high wire stiffness tends to exacerbate the problem of "poke-through" by preventing the wire from returning to its natural state once it has been bent. Even if such a wire starts out straight it can be permanently kinked due to bending or folding.

The tightness of the weave or braid will also impact the degree on wire "poke-through." A tighter braid will obviously minimize poke-through, but at the cost of a stiffer overall cable. The final factor, which is particularly important during hex-abrasion testing, is slippage between the textile and wires. If the wires and textile are not consistently in contact with each other, the textile tends to bunch in some locations and spread out in others. The bunching significantly reduces the wires' lateral support and makes it much easier for them to buckle and poke through the textile. This problem can be addressed by increasing the friction between the wire and textile through the use of a tighter weave/braid, adhesives, or changing the wire insulation to one with a higher coefficient of friction.

As was mentioned earlier in subsection 3.2.1.4.3, the USB v2 was designed in part to improve upon the abrasion resistance of its predecessor by reducing the problem of conductor poke-through. The conductors used in this new design were significantly more flexible than those used in the USB v1. The resulting cable was more flexible and uniformly flat, with significantly fewer kinks and poke-throughs. Changing to TPE insulation also had the effect of increasing the friction between the power pair and the textile. Slippage was reduced to the point that even using a pair of pliers it was extremely difficult to pull the conductors out of a relatively

short length of cable. We believed that the friction increase would reduce the problem of slippage between the wire and textile.

When specimens of the USB v2 were subjected to hex abrasion testing we found that wire poke-through was still observed (Figure 34) but progressed more slowly than in earlier tests conducted with USB v1 cables. Slippage between the wires and textile was confined locally to the area of abrasion and would not be affected by connectorizing the cable ends. Once wires in the new USB design were exposed they did not stand up as well to abrasion as those in the earlier USB design.

Figure 34. Effect of 2000 cycles of hex-abrasion testing on USB v2 cable

3.2.2.2 Determination of Cable Stiffness

Initial Testing

In order to gain acceptance by the end user, a narrow woven cable must not detract from the wearability of the garment through which it is routed. The data cable must be as flexible as possible while maintaining durability so as not to impede human movement. The stiffness of a strip of cloth or data cable can be easily measured, without the need for specialized equipment, by using the Hanging Heart Loop Method. While numerous other techniques exist to measure stiffness, this method is one of the simplest and least expensive available. In this test a 10 in. strip of the material to be tested is taped to a bar (Figure 35). The distance from the top of the bar to the lowest point of the heart shaped loop is measured using a Micro-Vu optical comparator 2 min after the specimen has been taped in place. While the test standard specifies that all deflections should be measured using a ruler, this technique was found to be highly inaccurate. The optical comparator on the other hand was accurate to within 0.001 in.

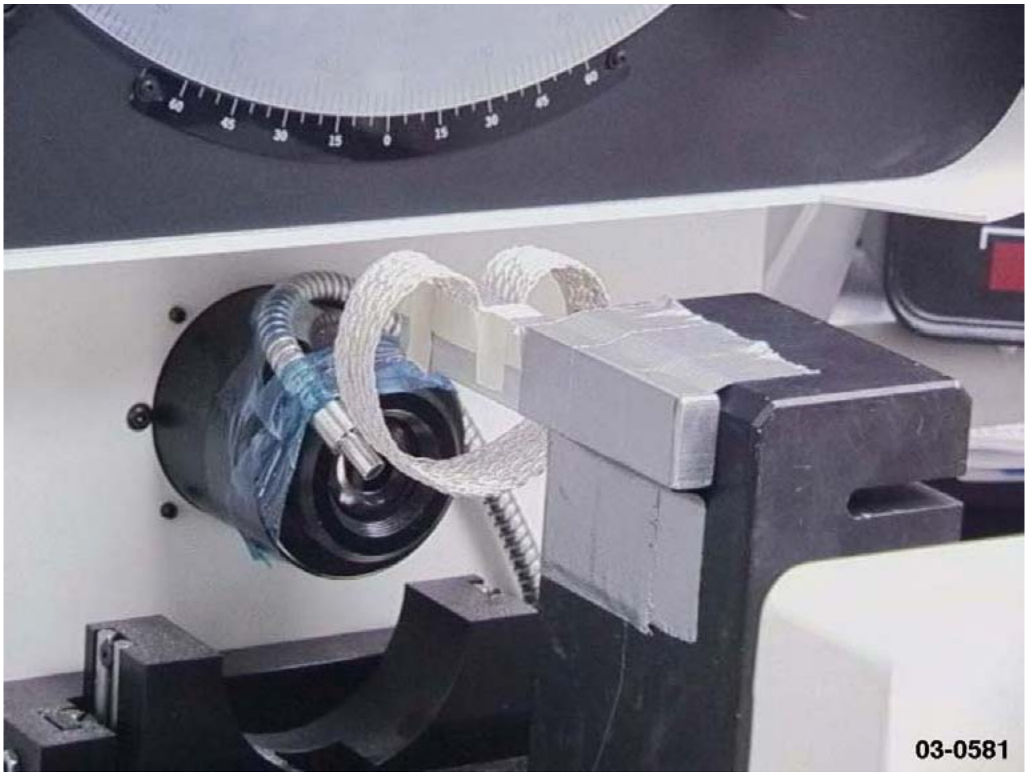


Figure 35. Initial setup for stiffness test measurements

The Hanging Heart procedure was repeated with successively larger weights hung from the bottom of the loop. The specimens were tested for bending in the two directions (positive and negative bending moment) and the results were averaged together. Three duplicate specimens were tested in this manner for each cable design. The result is a plot of load versus displacement as shown in Figure 36. The slope of this curve is the stiffness of the sample. Table 10 provides a brief description of the textile structures investigated in this section. Due to the wide variety of observed load response curves it was necessary to use the following criteria when calculating stiffness:

- To allow us to make general stiffness comparisons between all types of textile materials, we measured the slope over a relatively narrow deflection range (2.5 in. to 3.0 in.) that was common to all materials (Figure 36).

- For stiffness measurements within a group of similar materials, such as electrotextile buses (cables), a wider deflection range can be used to determine stiffness (i.e., 2.0 in. to 3.0 in.) as shown in Figure 37. By using a wider data range we were able to get more accurate stiffness measurements (Figure 38). For electrotextile buses these stiffness measurements are designated K_b to distinguish them form the more general stiffness measurements designated K.

These initial stiffness testing results showed that standard electro-optic components contribute a significant portion of the overall cable stiffness. As discussed earlier in subsections

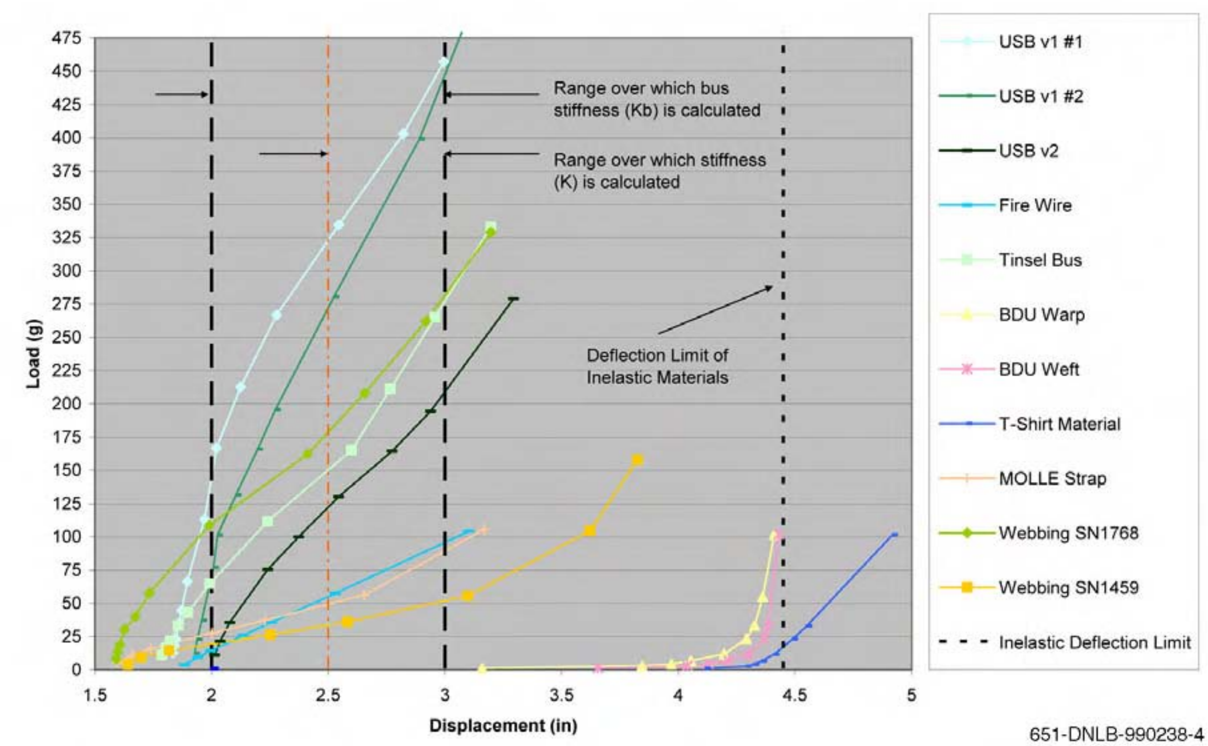


Figure 36. Load deflection curves for buses, antennas, webbing, ribbons and clothes. (The testing of antenna materials was done under Contract No. DAAB07-01-C-L710 and is included for sake of completeness)

Table 10. Description of textile specimens used during stiffness testing

Item	Description
Tinsel Bus	The cable with tinsel wire conductors that was developed in Phase I (4)
USB v1 No. 1	The first run of the woven nylon USB v1 (see subsection 3.2.1.4.2)
USB v1 No. 2	The second run of the woven nylon USB v1 (see subsection 3.2.1.4.2)
USB v2	A more flexible woven nylon cable (see subsection 3.2.1.4.4)
5-Conductor Cable	Similar to USB v2 but narrower and with an extra power wire (see subsection 3.2.1.4.4)
USB v3	A woven nylon cable using Aracon® conductors (see subsection 3.2.1.4.5)
Fire Wire	A braided cable with electro-optic elements (see subsection 3.2.1.5)
Round USB Cable	The standard cable as specified by the USB 2.0 specification
BDU	Fabric from a standard BDU garment
T-Shirt	Material from preshrunk 100 percent cotton jersey knit T-shirt
MOLLE Strap	Webbing from a standard MOLLE vest
Webbing (SN 1768)	A plain weave, Nomex®/Kevlar® webbing from Offray
Webbing (SN 1459)	A plain weave, polybenzimidazole (PBI)/Kevlar® webbing from Offray
Plastic Optical Fiber	The POF used in the braided Fire Wire cable (see subsection 3.2.1.5)

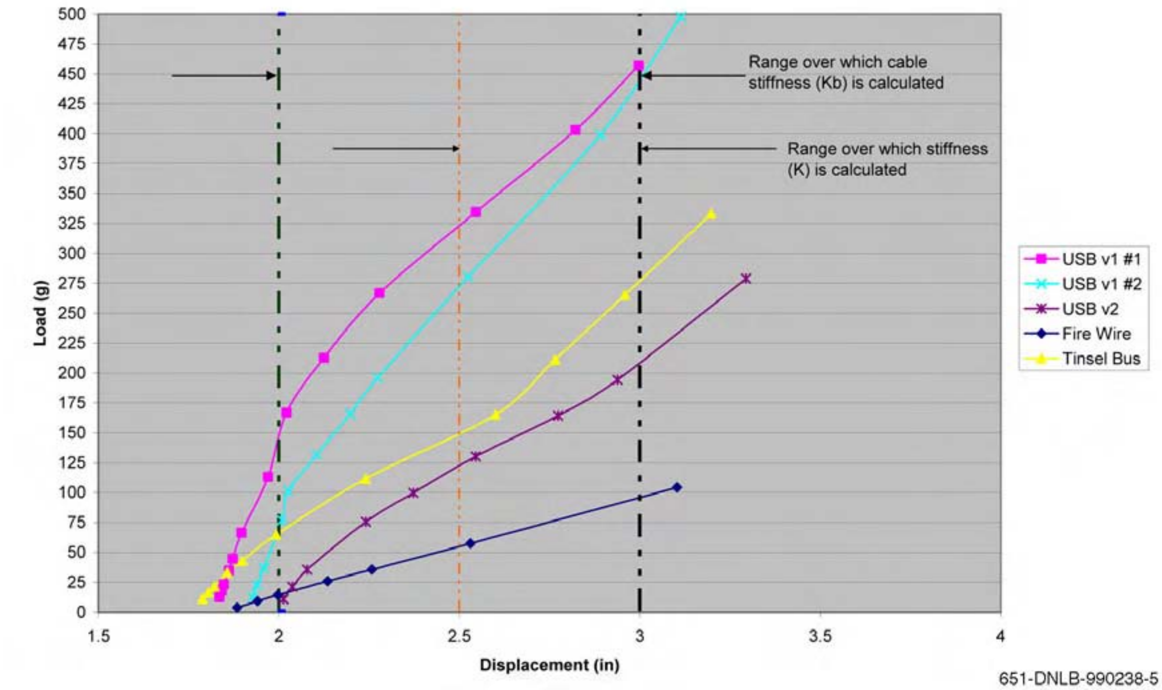


Figure 37. Data range used to determine data bus stiffness K_b

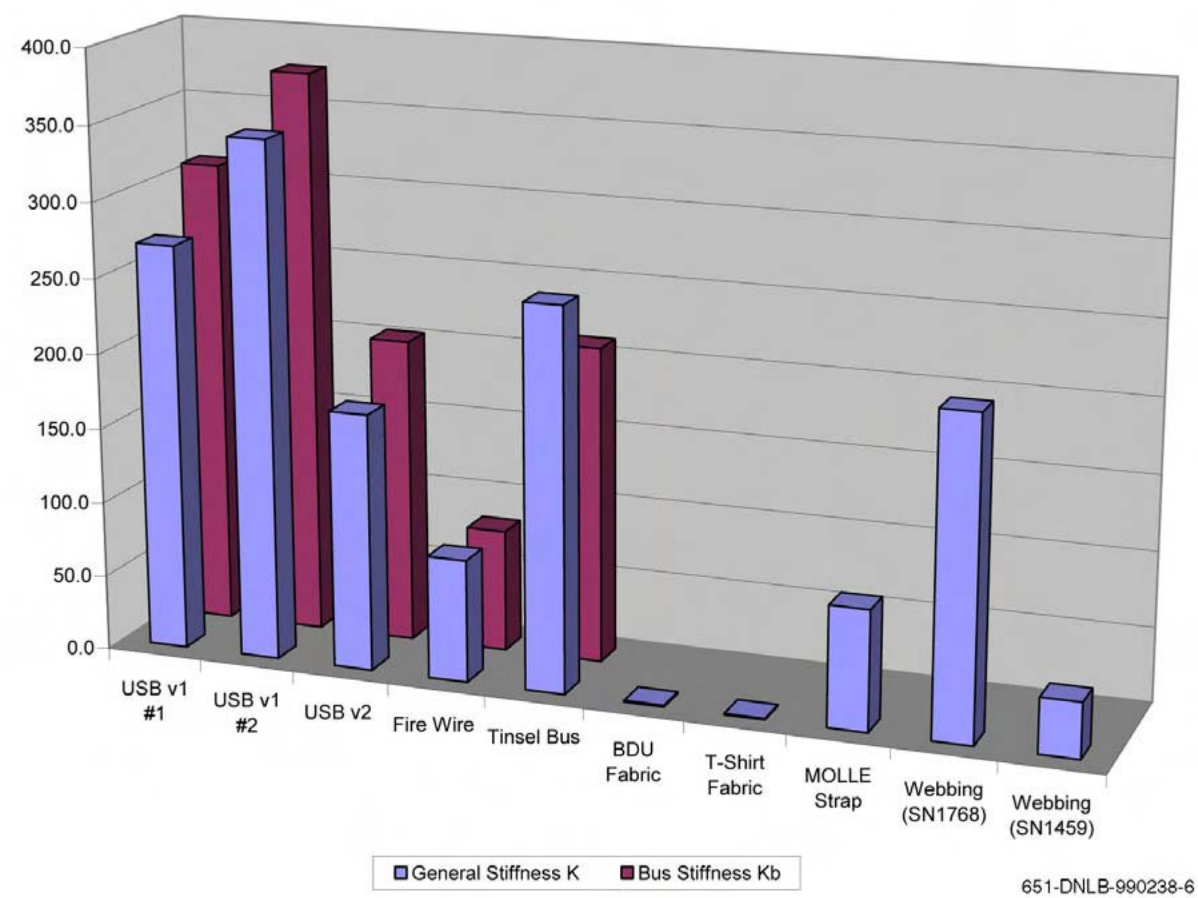


Figure 38. Stiffness measurements for bus designs, fabrics, webbings

3.2.1.4.3 and 3.2.1.4.4, several ways in which we could decrease the stiffness of these components were identified:

- Use softer, lower durometer, insulations on all wires.
- Use highly stranded conductors.
  - Standard Copper.
  - Metallized Textile Fibers.
  - Metal Clad Textile Fibers.
- Replace the standard foil shielding with a hollow braid of metal clad fibers.

Using these design guidelines three new highly flexible cables were developed; the USB v2, USB 3 and a 5-conductor version of the USB v2 (Figure 39). Descriptions of these cable designs were provided previously in subsections 3.2.1.4.4 and 3.2.1.4.5.

Refinement to Testing Procedure

We observed during the initial round of stiffness testing that at higher loads the tape used to secure the specimens, a method prescribed in the test specification, was insufficient to keep the

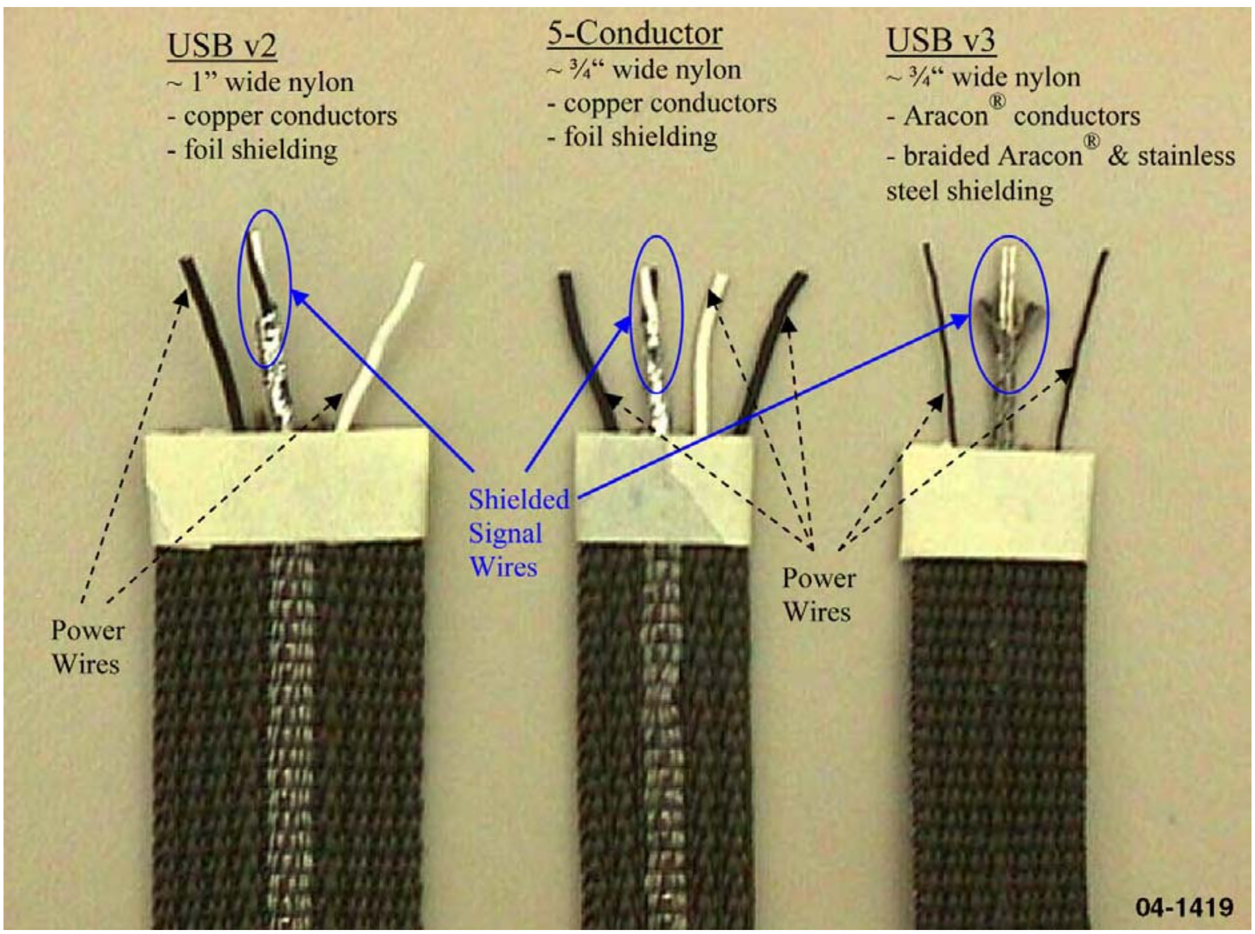


Figure 39. Three electrotextile cables developed using initial stiffness testing data

specimen from pulling away from the crossbar (Figure 40). This deflection had the effect of altering the measured stiffness values. The problem was corrected by securing the specimens with metal bars held in place with bolts (Figure 41). Accuracy was further improved by making sure that initial deflection of each specimen started at approximately the same value. This technique is only viable for textiles that behave in a plastic or malleable manner such as cables that contain copper wires.

Once the test setup and procedure had been fine tuned three specimens of each data cable were tested as discussed previously. These cables included USB v1 to v3, the 5-conductor cable and, for reference a standard off the shelf USB cable. The resulting load-deflection curves were used to measure each specimen's stiffness over as wide a range of deflections as possible, which in this case was 1 in. (1.7 in. to 2.7 in.). Figure 42 shows the averaged load-deflection curves obtained for each cable type. The average stiffness measurements are shown in Figure 43.

This data shows that in simply going from a standard round polymer cable to a flat textile cable we were able to reduce stiffness by 45 percent without making any changes to the specified conductive elements. The changes described earlier in going from USB v1 to USB v2 resulted in a 77 percent reduction in cable bending stiffness relative to a standard round USB cable. By trimming the cable width from 1 in. to 3/4 in. the 5-conductor MILES cable was able to reduce stiffness by 81 percent that of standard USB cable, despite the fact that it contained an additional power conductor. The USB v3 cable was expected to have the lowest stiffness due to its narrow width (3/4 in.) and use of Aracon® as the conductor. Figure 43 shows, however, that it performed

Figure 40. Close-up of weighted specimen secured with tape

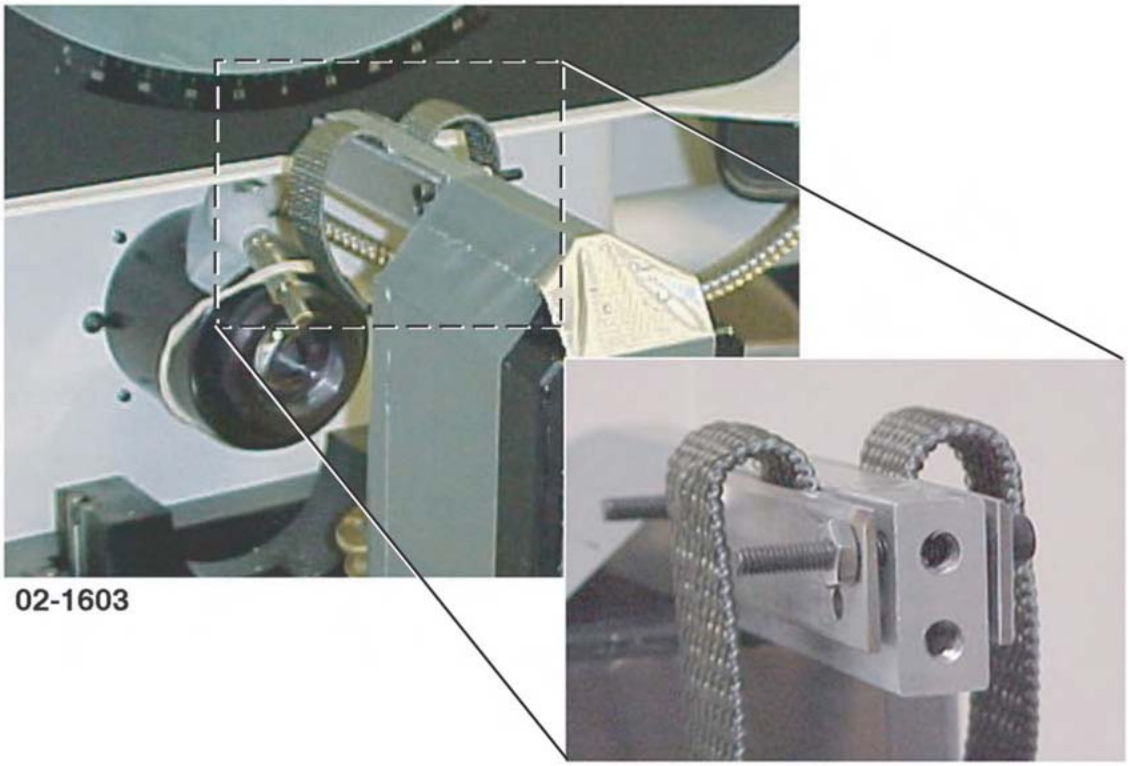


Figure 41. Close-up of weighted specimen secured with steel bars

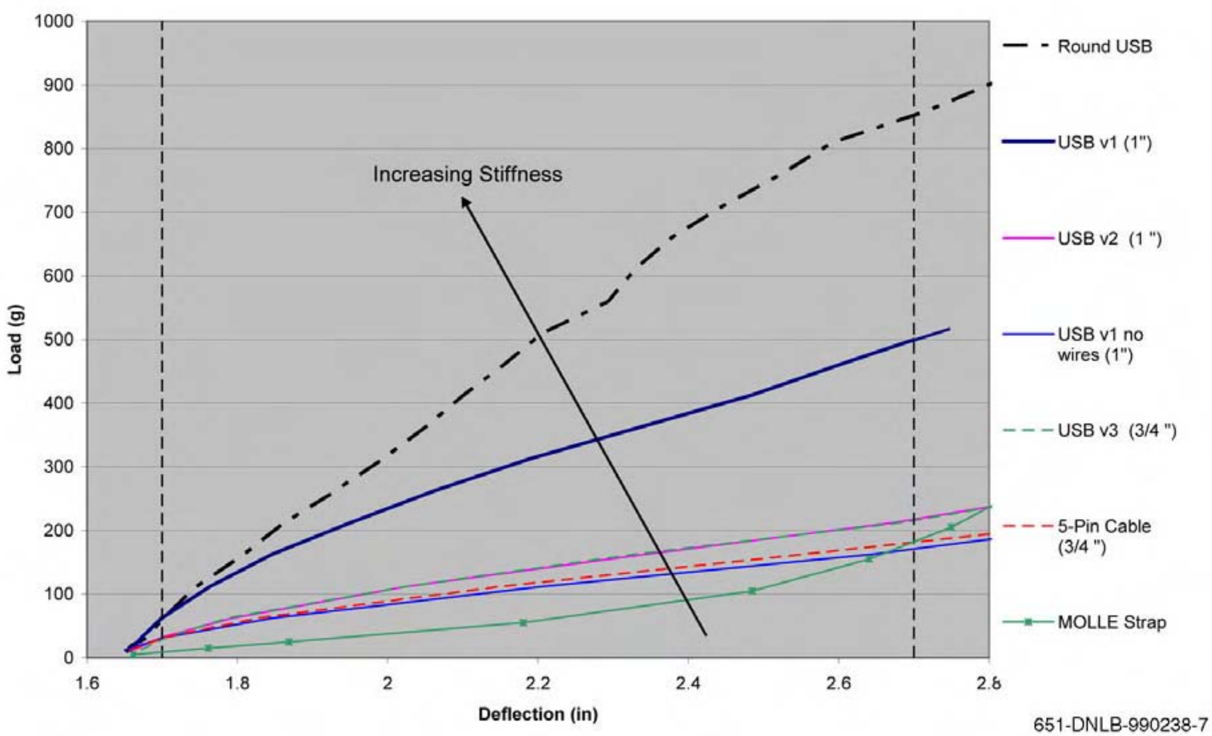


Figure 42. Averaged load-deflection curves for all cable specimens

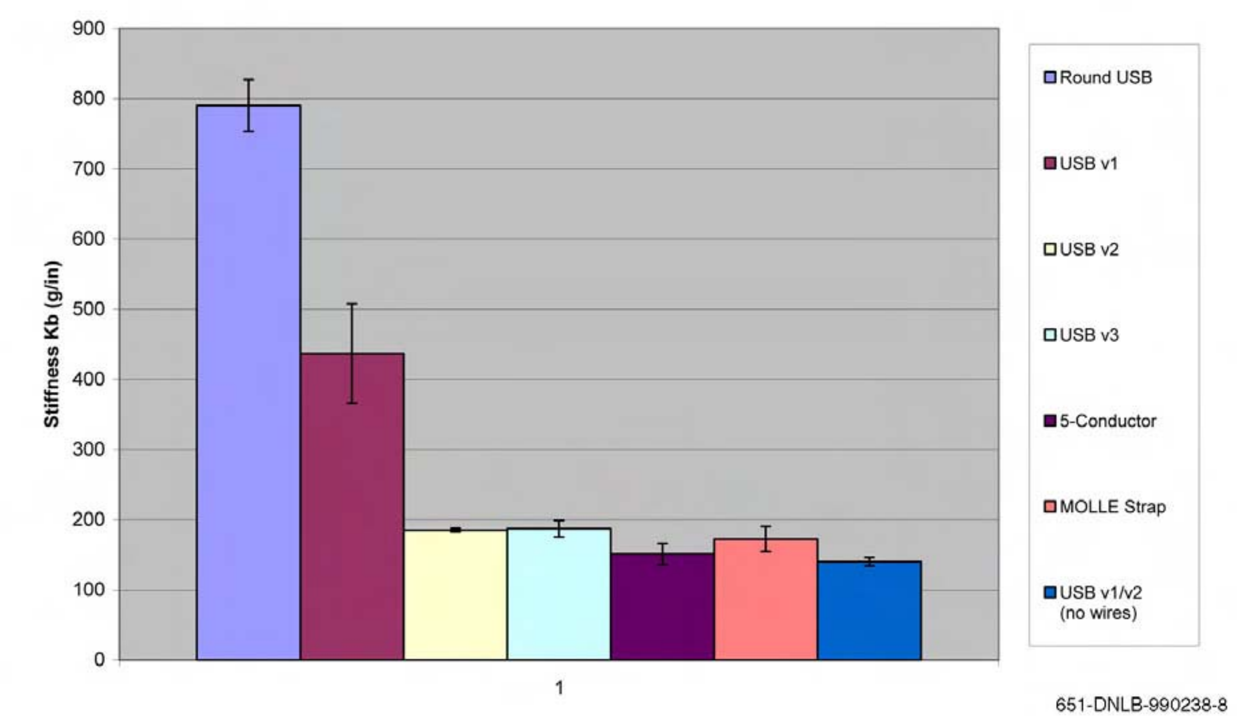


Figure 43. Average bending stiffness for all cable designs

the same as the wider USB v2, which also contained larger diameter wires. We have attributed this result to the high stiffness of the Tefzel® used to insulate the Aracon®. Investigations are currently underway to find highly flexible insulation materials that are compatible with the Aracon® manufacturing process.

3.2.2.3 Tensile Strength Testing

To determine the loads and cycle rates to be used in the fatigue, some preliminary tensile strength tests were performed. These tests gave us the ranges of the ultimate strength and modulus of the cables under consideration. The two cable designs of primary interest at this stage were the USB v1 and Firewire. For both cable designs three specimens were tested to failure on the Instron using the ASTM-D4268 test standard. In these tests, the specimens were mounted directly in the Instron's grips as shown in Figure 44. The results of these tests (Figure 45) showed the USB and Firewire cables to have ultimate strengths of 1100 to 1200 lb and 200 to 250 lb, respectively. In addition to ultimate failure the USB v1 and Firewire cable designs seem to undergo a preliminary failure at 35 percent and 60 percent of max load, respectively. We observed from failed specimens that the method of gripping the cables led to stress concentrations in certain regions of the textile. As a result, the textile began to tear unevenly resulting in lower values of tensile strength and stiffness. To overcome this testing problem, the specimens were mounted to a U-bolt fixture as shown in Figure 46. The cable was sewn in place with a high strength nylon thread. This arrangement allowed the load to be distributed evenly across the textile and the wires. As a result the measured tensile strengths are noticeably higher for both the USB v1 and Firewire cables with values of 2000 lb and 500 lb, respectively (Figure 47).

Figure 44. Tensile test specimen mounted directly to Instron grips

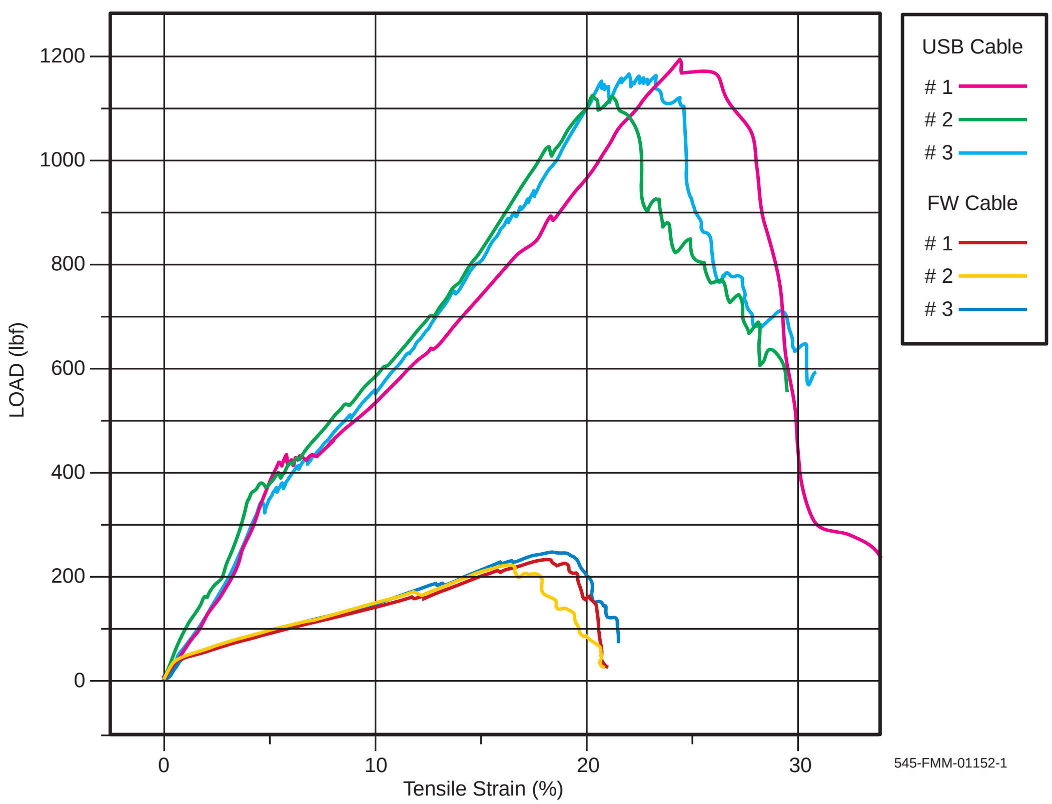


Figure 45. Tensile strength of USB and Firewire narrow woven buses using mechanical grips

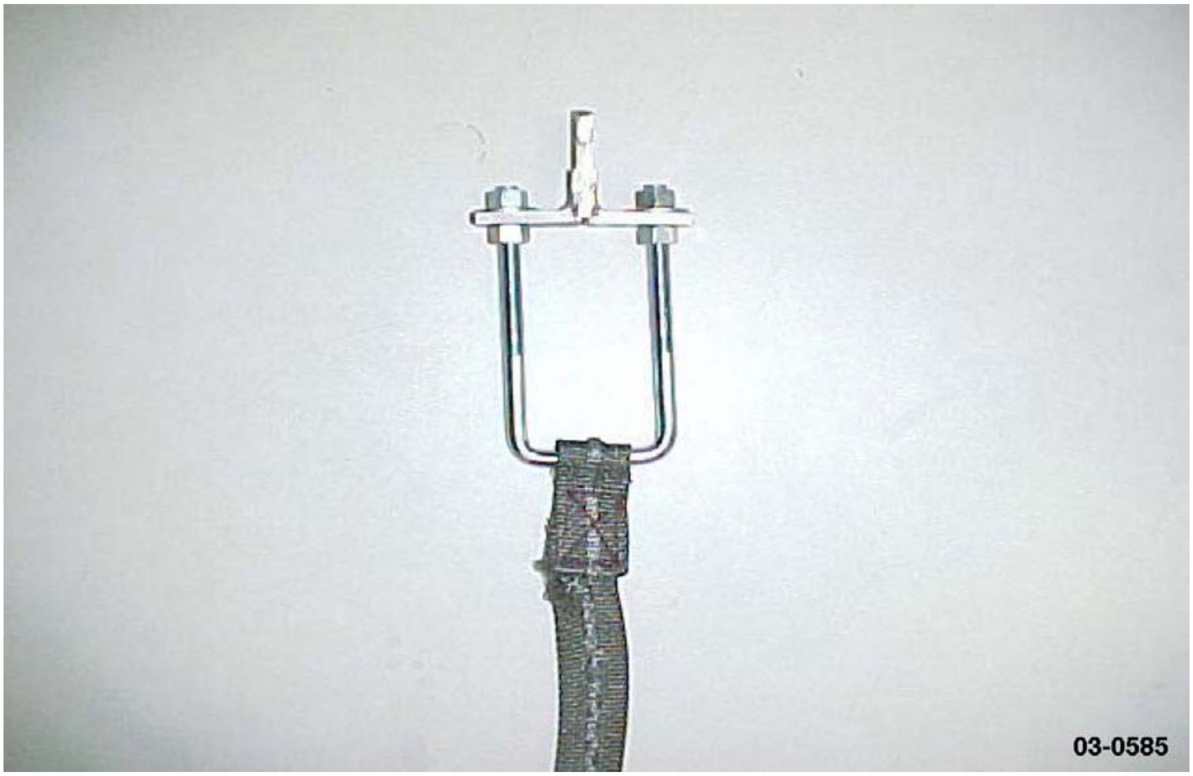


Figure 46. Tensile test specimen sewn to U-bolt mount for even distribution of load

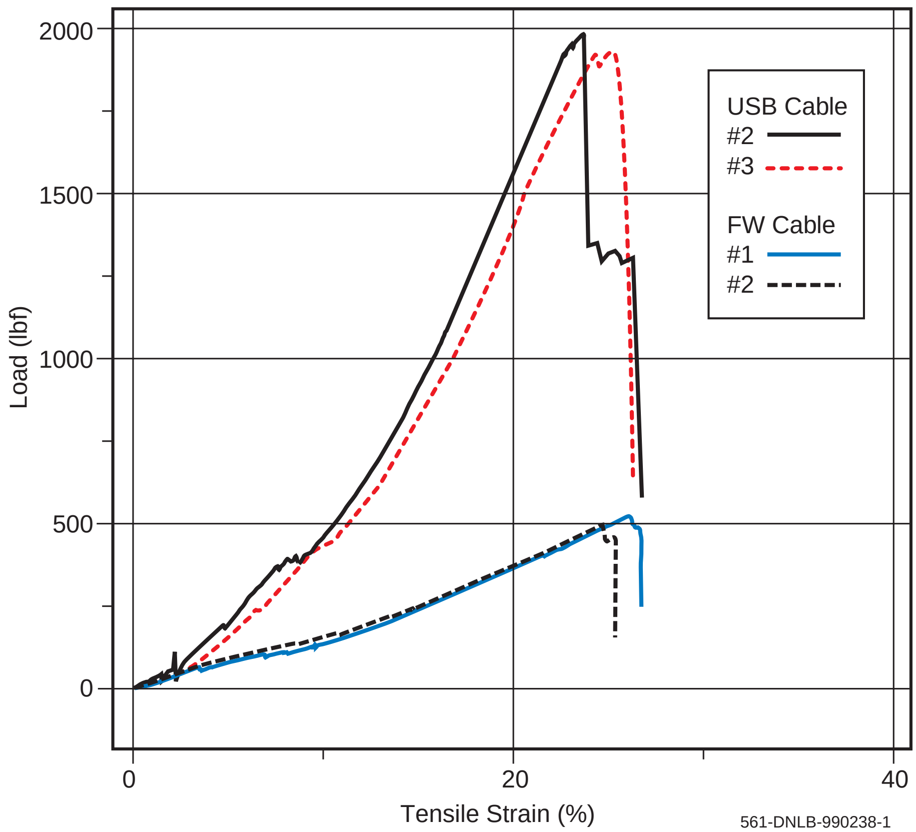


Figure 47. Tensile strength of USB and Firewire narrow woven buses using U-bolt fixture

Lengths of USB v1 were also sent to Exponent (Phoenix, AZ) and tested using the tensile strength test setup shown in Figure 48. The test results for the USB v1, a PAN cable from the Land Warrior 0.6 system and a Beldon M-9535 cable are shown in Figure 49. This data shows that the Foster-Miller textile USB v1 cable is an order of magnitude stronger in tension than cables currently used to connect soldier worn military assets.

3.2.2.4 Tensile Fatigue Testing

We have estimated that a data bus will have to be able to withstand several hundred thousand deformation cycles. Repeated tensile and bending deformations are particularly important to consider. The first step in setting up a test procedure that measured fatigue was to determine the maximum tensile strength and modulus of the narrow woven cables as discussed previously. Using this information a reasonable load cycle was determined for both tensile and bending fatigue tests.

The effects of tensile fatigue were investigated first using an Instron; the test used here is not a standard method. The test setup is shown in Figure 50. The cable specimens were secured to U-bolt fixtures in the same manner as the specimens used in the tensile strength tests. Specimens were tested by cycling between 0 and 250 lb for 5k, 10k, 20k and 40k cycles. A sample of the testing cycle data is shown in Figure 51. Due to the elastic nature of the specimens, a cycle rate greater than 0.1 Hz was not feasible. As a result testing beyond 40k cycles was deemed to be prohibitively expensive and time consuming.

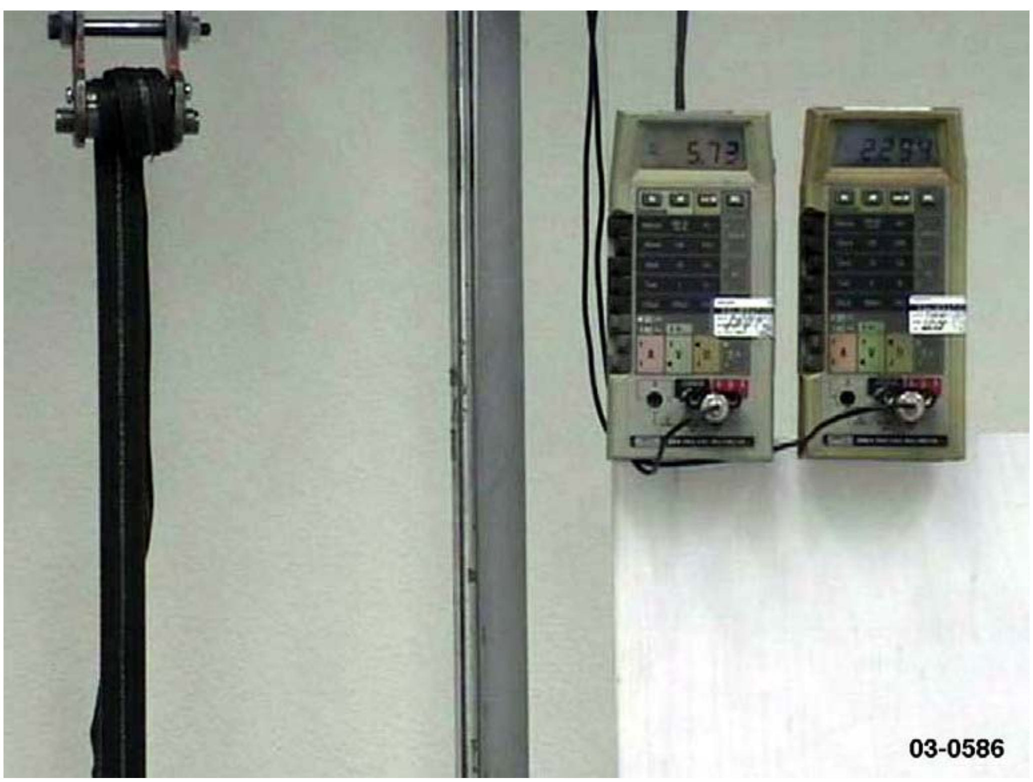


Figure 48. Exponent's tensile strength testing setup

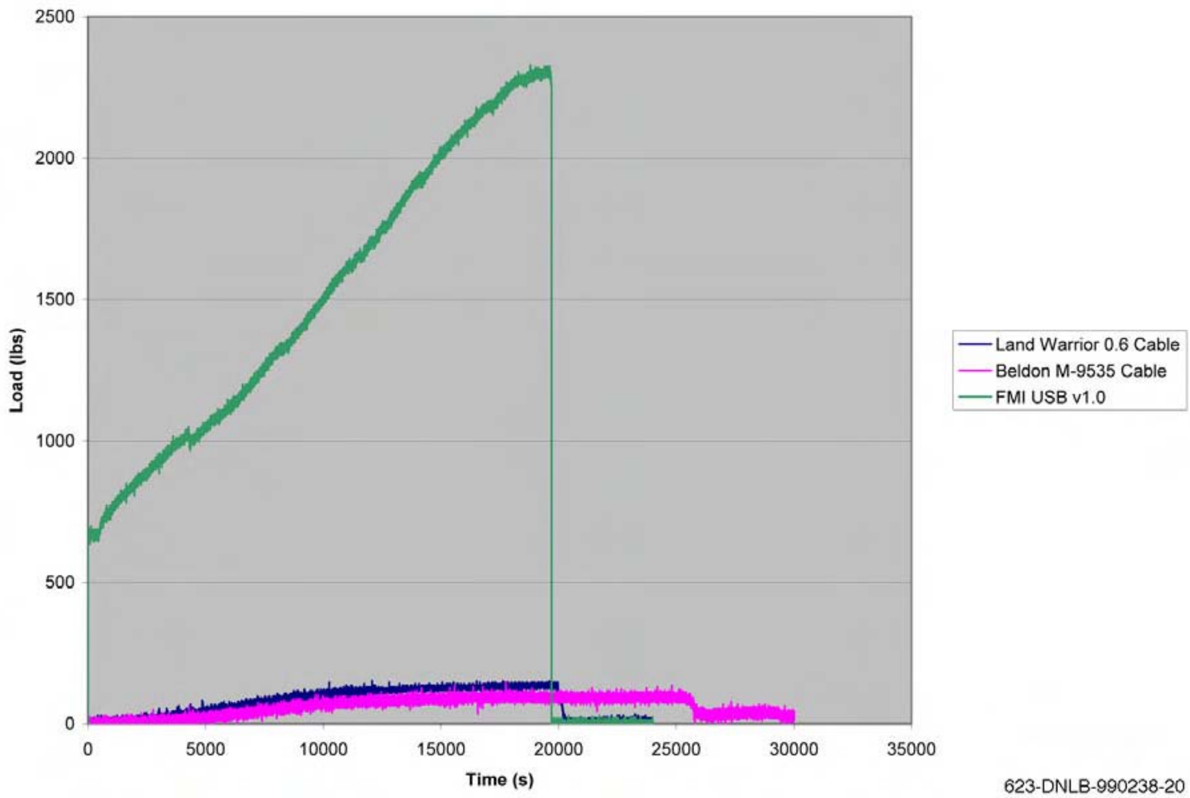


Figure 49. Tensile strength of USB v1 cable and other relevant cable designs

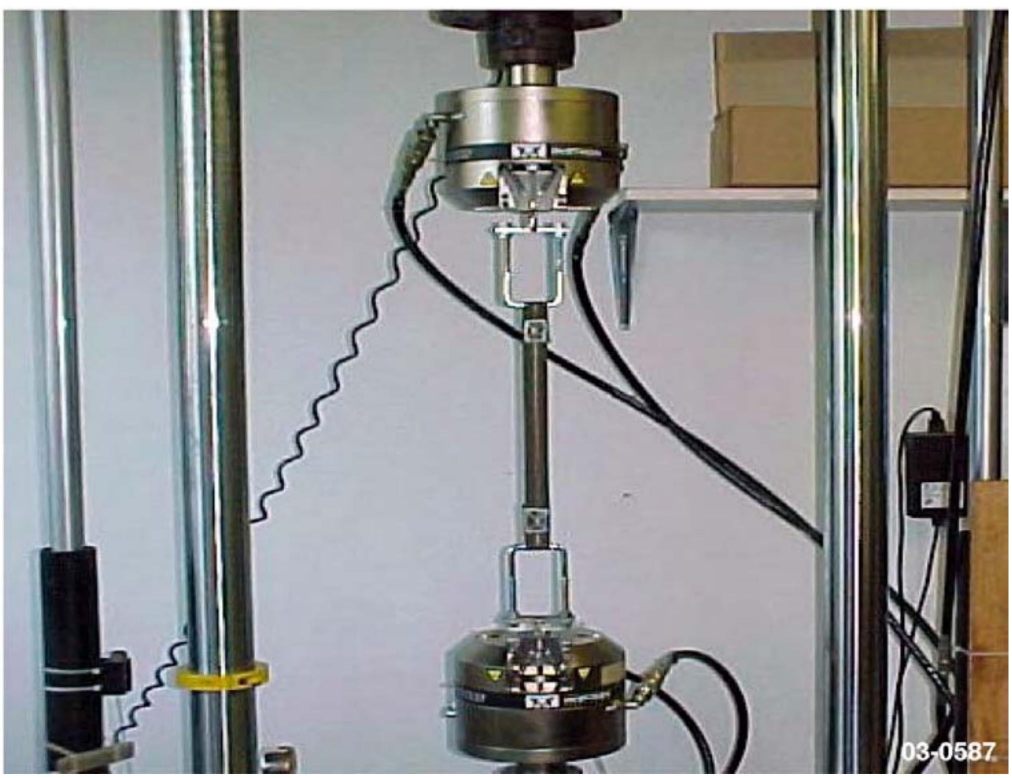


Figure 50. Tensile fatigue test setup

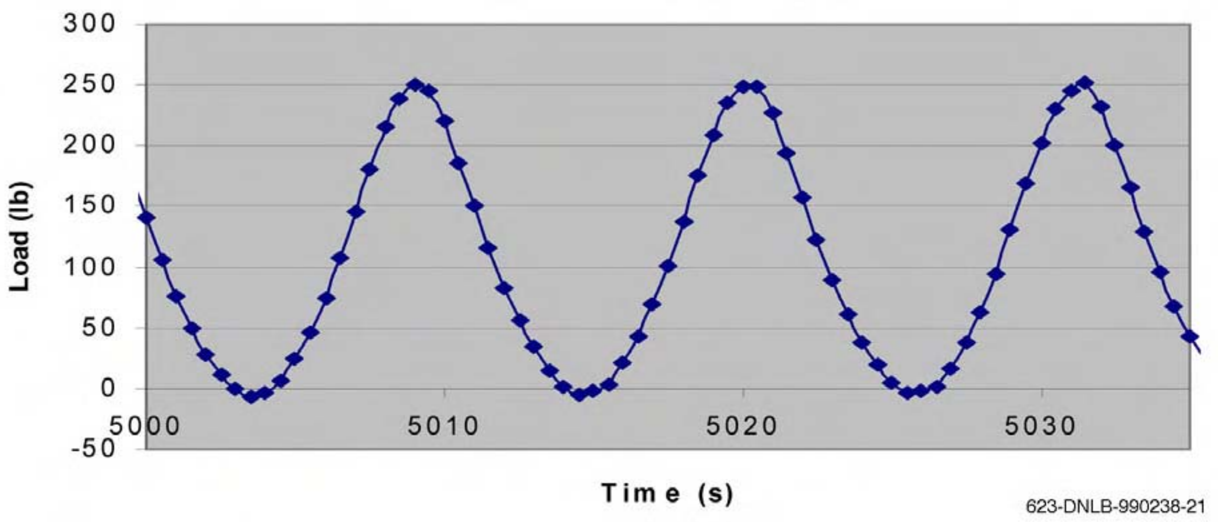


Figure 51. Typical loading profile used in tensile fatigue tests

After testing was completed the specimens were sent to Contech Research for signal integrity evaluation. The evaluation results indicated that the specimens were compliant with USB signal integrity requirements even after 40k cycles (Table 11).

Table 11. Signal integrity test results for tensile fatigue specimens

Test	Requirements	5k Cycles	10k Cycles	20k Cycles	40k Cycles
Examination	No damage	Pass	Pass	Pass	Pass
Impedance	76.5 to 103.5	Pass	Pass	Pass	Pass
Attenuation	3.2 dB and 5.8 dB maximum between 200 and 400 MHz	Pass	Pass	Pass	Pass
Propagation Delay	5.2 nS/m maximum	Pass	Pass	Pass	Pass
Propagation Delay Skew	100 pS maximum	Pass	Pass	Pass	Pass
Capacitive Load	200 to 450 pF	Pass	Pass	Pass	Pass

3.2.2.5 Bending Fatigue Tests

The effect of repeated bending deformation was tested on an Instron using the Cyclic Bend Over Sheave (CBOS) test shown in Figure 52. A series of technical issues dogged this phase of testing and resulted in the pneumatic control system having to be entirely rebuilt. The primary problem was found to be a faulty line of pneumatic valves that were assembled improperly at the supplier's factory. The distributor replaced these valves with a different model and testing was completed.

Two replicates of the USB v1 cable were tested for 35k bending fatigue cycles loaded between 125 and 300 lb. Both sets of specimens were found to perform well within the USB signal integrity specifications. A typical loading profile experienced by the cables is shown in Figure 53. After testing was completed the specimens were sent to Contech Research for signal

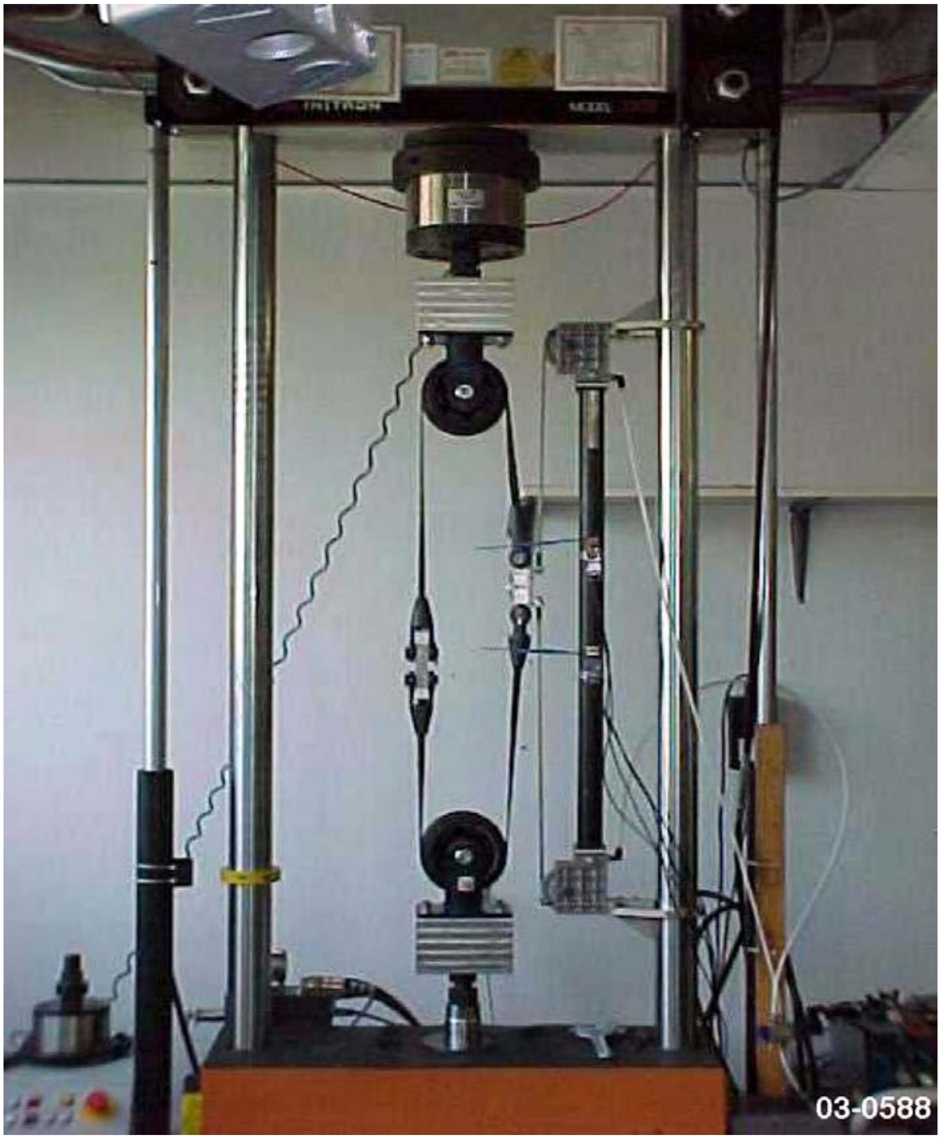


Figure 52. Bending fatigue test setup

integrity evaluation. The evaluation results indicated that the specimens were compliant with USB signal integrity requirements even after 35k cycles (Table 12).

3.2.2.6 Impact Testing

In order to assess the USB cable's ability to withstand blunt trauma incidents, a series of impact tests was performed. The first step was to determine the kinetic energy a cable was likely see during such an accident. Since the number of possible scenarios involving blunt trauma are virtually limitless, this task was not simple. To make it manageable, the case of a soldier running, tripping and impacting an object such as a rock was used as the model scenario.

To determine the kinetic impact energy this scenario would generate, we determined the mass of the fully equipped soldier and the velocity with which he hits the ground. Wherever

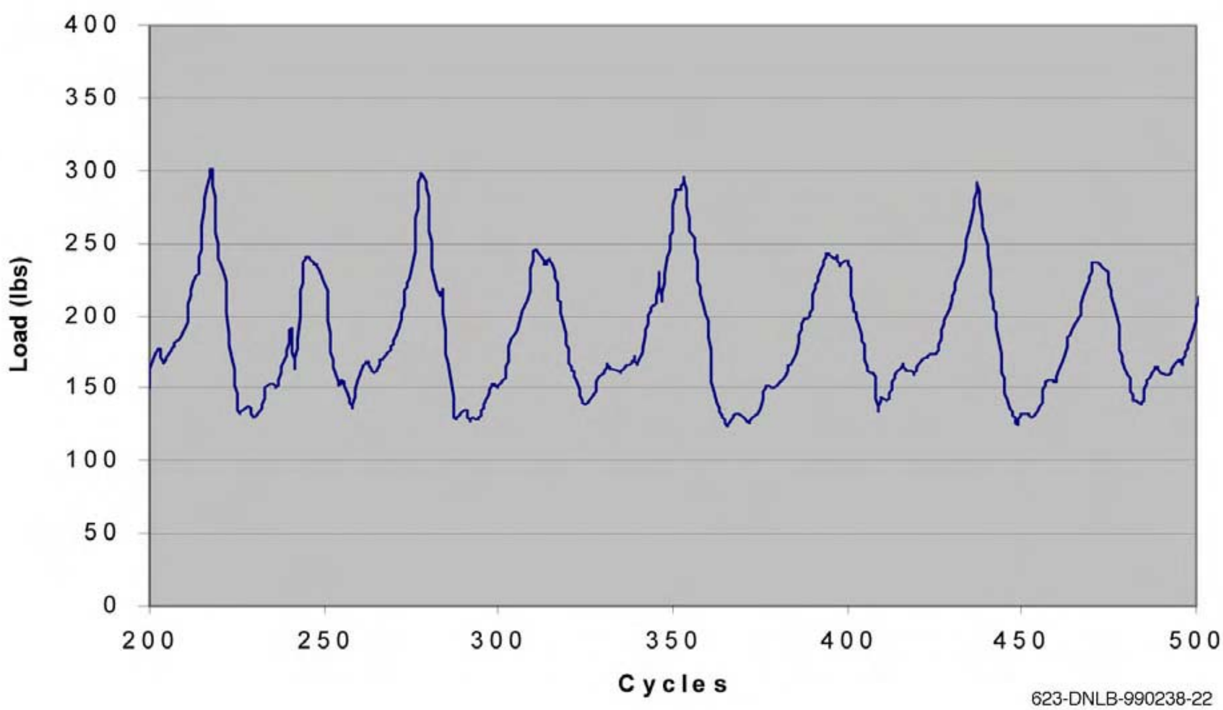
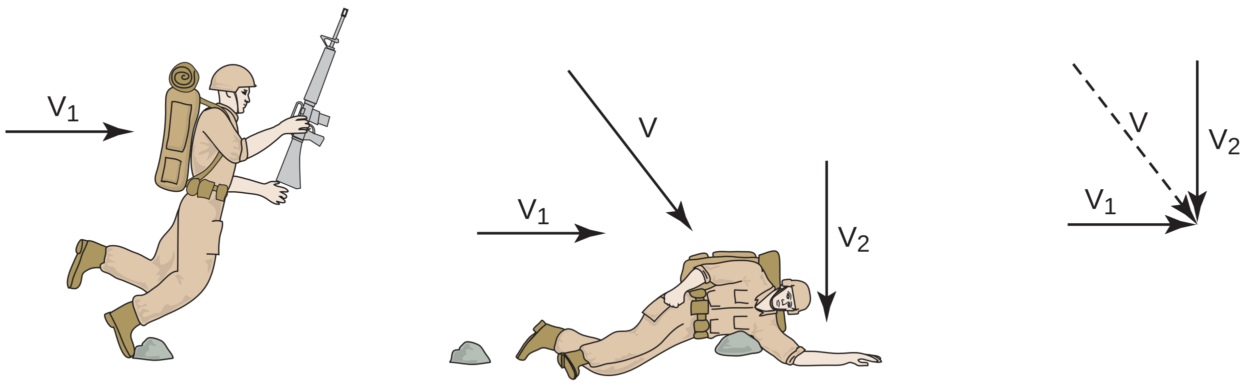


Figure 53. Example load profile from cyclic bend testing

Table 12. Cyclic bend fatigue testing of USB v1 textile cable

Test	Requirements	35k Cycles
Examination	No damage	Pass
Impedance	76.5 to 103.5	Pass
Attenuation	3.2 dB and 5.8 dB maximum between 200 and 400 MHz	Pass
Propagation Delay	5.2 nS/m maximum	Pass
Propagation Delay Skew	100 pS maximum	Pass
Capacitive Load	200 to 450 pF	Pass

assumptions regarding input data were necessary, values were chosen that would yield the greatest impact energy. The weight of the soldier's equipment was assumed to be 71.7 lb (32.5 kg), the same as the Land Warrior 1.0 system. The soldier was assumed to be a 95th percentile, 6 ft 1.5 in. (1.87m) male, weighing 216 lb (98 kg). This assumption yielded a total weight of 287.7 lb (130.5 kg) for the fully equipped soldier. The soldier's impact velocity is made up of two components, the soldiers forward running velocity, V1, and downward falling velocity, V2, (Figure 54). Using data from a recent Physical Fightability Evaluation we determined that a soldier encumbered as mentioned above would have an average running speed of approximately 1.82 m/s. This data is from a 1/2 mile run collected after a 5 mile road march. We therefore assumed that a rested soldier could easily attain a sprint speed of 3 m/s for short periods of time, even while in full gear. To determine the downward velocity of the soldier at impact we need to estimate the distance, X_2 that his center of mass falls. Once this calculation was done both components of the soldiers velocity vector could be resolved into a single impact velocity from which the impact energy was determined (Figure 54). Getting an estimate of X_2



$$V = \sqrt{V_1^2 + V_2^2}$$

$$V_2 = gt$$

$$X_2 = \frac{1}{2}gt^2 = \frac{1}{2}g\left(\frac{V_2}{g}\right)^2$$

$$\therefore V_2 = \sqrt{2X_2 g}$$

$$V_1 = \text{Defined}$$

$$T = \frac{1}{2}mV^2$$

V_1 = Forward Velocity

V_2 = Falling Velocity at Time of Impact

X_2 = Distance from Ground to Center of Gravity of Fully Equipped Soldier

g = Gravitational Acceleration

T = Kinetic Energy of Impact

m = Mass of Fully Equipped Soldier

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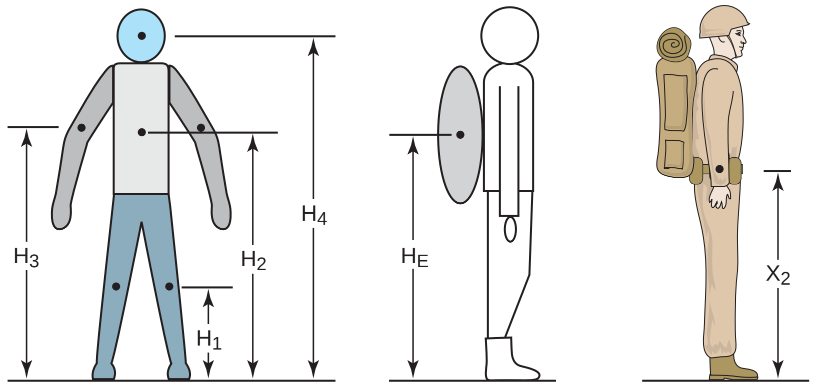
Figure 54. Determination of maximum impact energy

however was not a simple matter. Using anthropometric data describing the percentage of weight in each region of the human body, measurements of the distance from the ground to the center of mass of each of these regions, and an estimate of the distance from the ground to the center of mass of the soldier ensemble, it was possible to estimate a value for X_2 of 1.09m (Figure 55). Using this data we were able to calculate an impact velocity of 5.03 m/s and an impact energy of 1653 N•m. These values are equivalent to the fully equipped 130.5 kg soldier dropping straight down from a height of approximately 1.3m. This information was then used by Orange County Material (OCM) Tests Labs (Anaheim, CA) to design an impact test setup similar to that shown in Figure 56.

Thirty-six connectorized USB cables were sent to OCM Test Labs for impact testing. This lot included both Foster-Miller USB v1 and USB v2 specimens overmolded with the original green Santoprene and the newer, more flexible, black Santoprene. Subsection 3.3.5 discusses connector design and material selection process. Table 13 shows the specimen test matrix along with pertinent data.

While designing the test setup, we realized that impact energy alone does not accurately describe the types of blunt trauma of concern here. Also of importance are the velocity and geometry of the impacting mass. At 1653 N•m (J) the maximum impact energy calculated in the



$$X_2 \cdot m = \sum_{i=1}^{4} H_i m_i + H_E m_E$$

$$X_2 = \frac{\sum_{i=1}^{4} H_i m_i + H_E m_E}{m}$$

X_2 = Distance from Ground to Center of Gravity of Fully Equipped Soldier

m = Total Mass of Fully Equipped Soldier

m_i = Mass of Region i of the Soldier

H_i = Distance from Ground to Center of Gravity of Region i of Soldier

m_E = Mass of Equipment

H_E = Distance from Ground to Center of Gravity of Equipment

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Figure 55. Center of gravity calculations and methodology

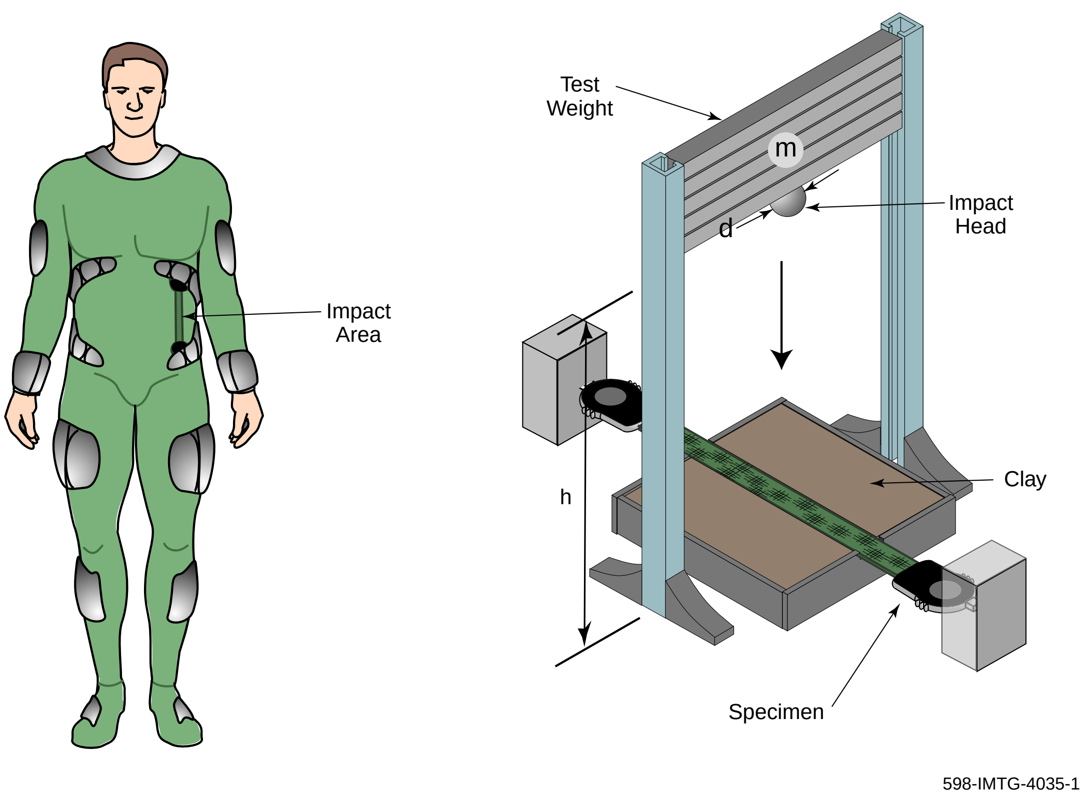

Figure 56. Impact testing

Table 13. Specimen test matrix (a description of shore hardness is presented in subsection 3.3.3)

Group ID	Cable Design	Cable Stiffness; K_b (g/in.)	Shore A Hardness of Santoprene Overmold	Specimen Quantity
1A	USB v1	436.7	90 (Green)	6
1B	USB v1	436.7	90 (Green)	6
2A	USB v2	184.9	90 (Green)	6
2B	USB v2	184.9	90 (Green)	6
3	USB v1	436.7	75 (Black)	6
4	USB v2	184.9	75 (Black)	6

above scenario falls squarely in the range of ballistic impact energies (Figure 57). We would not expect however that the cable be able to survive a gunshot. The small contact area and extremely high velocity of a bullet (Figure 58) will result in catastrophic failure of most structures that it encounters. This is due to the inertia of the object being shot, an object that resists deformation, particularly at higher velocities. As a result, the material is likely to suffer a shear failure in ballistic situations. At low velocities, such as those of concern here, the structure being impacted has more time to deform and is better able to absorb or disperse the kinetic energy. For these reasons we decided to design an impact test that had an impact velocity representative of that in the above scenario.

The impact test setup (Figure 59) used a 152 lb (69 kg) steel cylindrical weight mounted on guide rails to impact a steel sphere resting on the USB cable. The cable was draped over a 2 in. thick block of modeling clay that has been found to have ballistic and blunt trauma properties

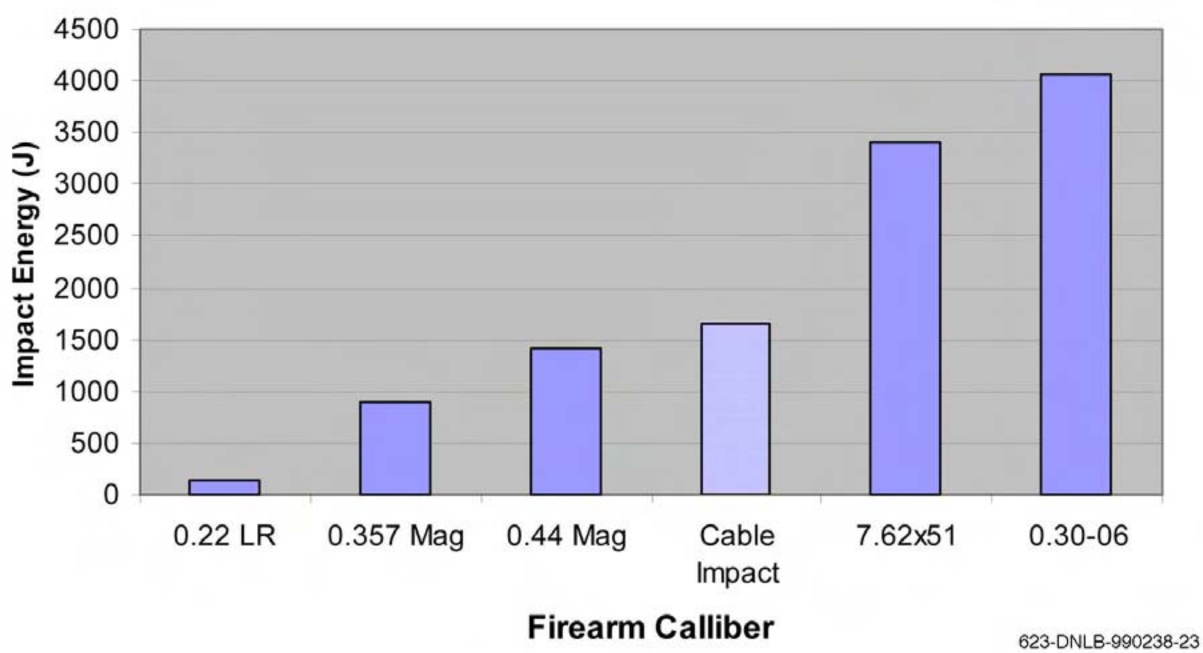

Figure 57. Comparison of the impact energy of common firearms rounds and Foster-Miller's cable impact test

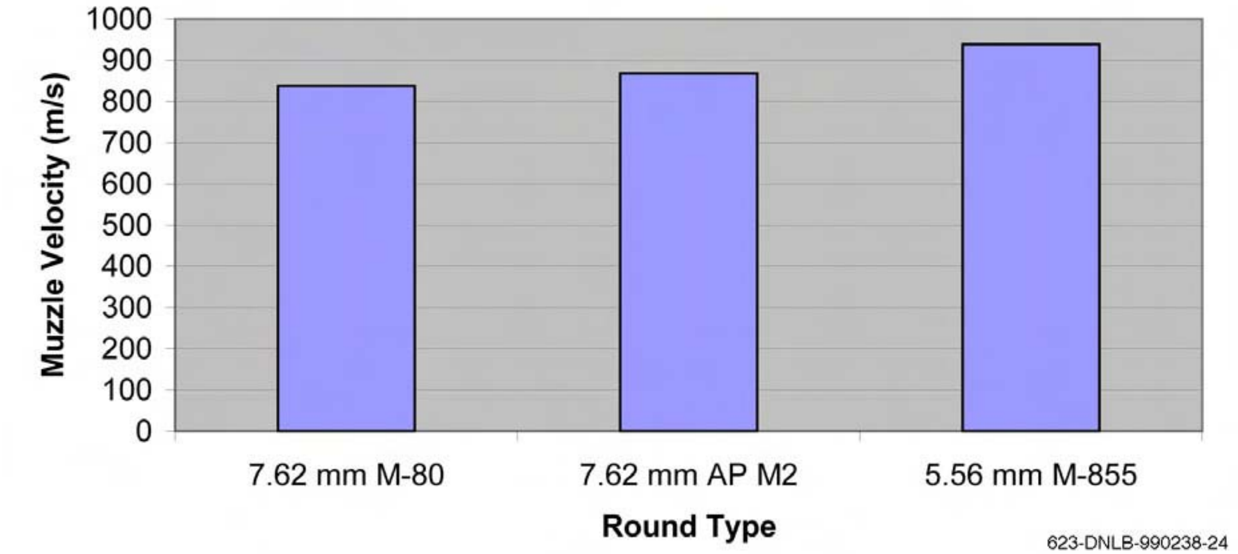

Figure 58. Muzzle velocities of common ballistic rounds

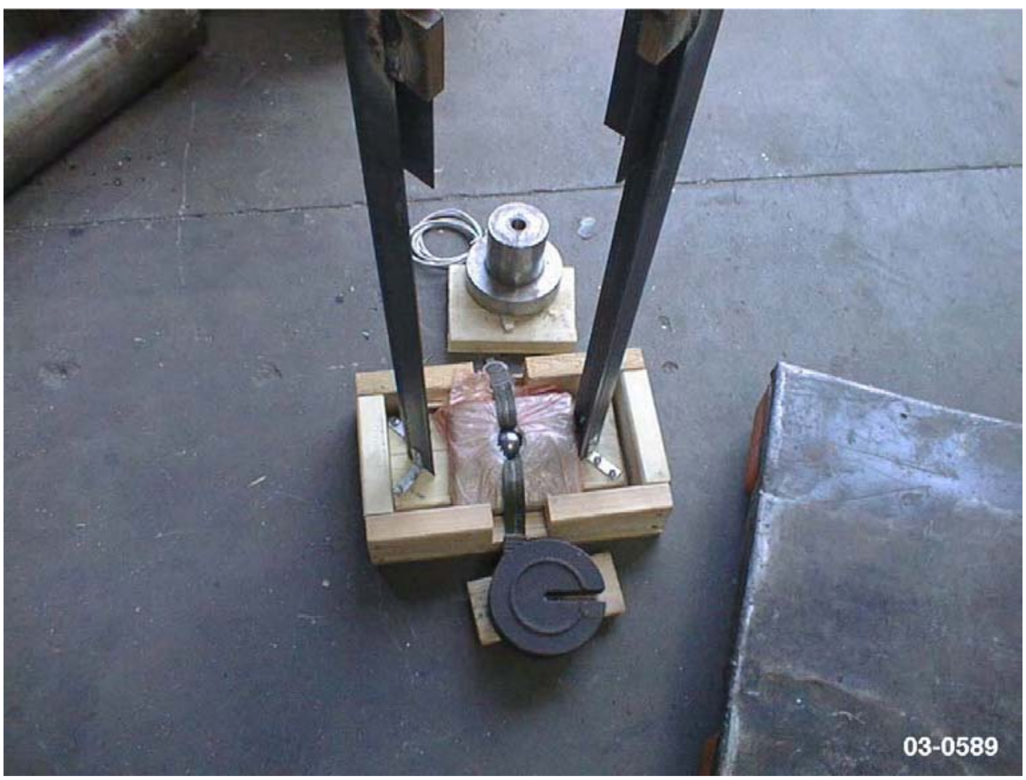

Figure 59. Impact test setup after impact

similar to that of the human body. Each end of the USB cable was plugged into a fixed USB socket to mimic its implementation in the soldier's Personal Area Network (PAN). From each group of 6 specimens, groups of 2 replicates were tested by dropping the weight from a height of 8 ft, 4 ft and 2 ft, respectively. The resulting impact energy and velocity are shown in Table 14. It can be seen that the range of impact velocities used in these tests cover the velocity calculated in our blunt trauma study. It is also apparent that the difference in velocities obtained for the

Table 14. Impact testing parameters

Scenario	Impact Energy	Impact Velocity
Running Blunt Trauma Scenario	1653J	5.03 m/s
Equipped Soldier Dropping from 4.24 ft (1.3m)	1653J	5.05 m/s
69 kg Dropped 8 ft (2.44m)	1650J	6.92 m/s
69 kg Dropped 4 ft (1.22m)	825J	4.90 m/s
69 kg Dropped 2 ft (0.61m)	412J	3.46 m/s

three drop heights is negligible and can be neglected for the purposes of this discussion. Initial tests indicated that the maximum impact energy used in this study (1650J) may be excessive as demonstrated by the damage done to the wood at the bottom of the tray of clay (Figure 60).

After all specimens were tested at OCM they were returned to Foster-Miller where they were inspected visually for signs of damage to the wires or webbing. The cables were then used to connect a digital camera to a laptop PC. Each cable was given a Pass/Fail based on whether it could transmit streaming video to the PC. This data was processed to look at the effects of design variables such as cable type and connector overmolding material as shown in Figure 61 and Figure 62, respectively. It came as somewhat as a surprise that the USB v2 cable and cables overmolded with black Santoprene had a higher incidence of failure. Since these design changes made the cable assembly more flexible it was felt that the cable would be better able to deform and hence dissipate the energy. One possible explanation for these observations is that the stiffer cable helps to distribute the impact energy more evenly through the clay substrate, thereby absorbing less energy itself. It should also be noted that sample size of specimens overmolded

Figure 60. Damage to experimental apparatus

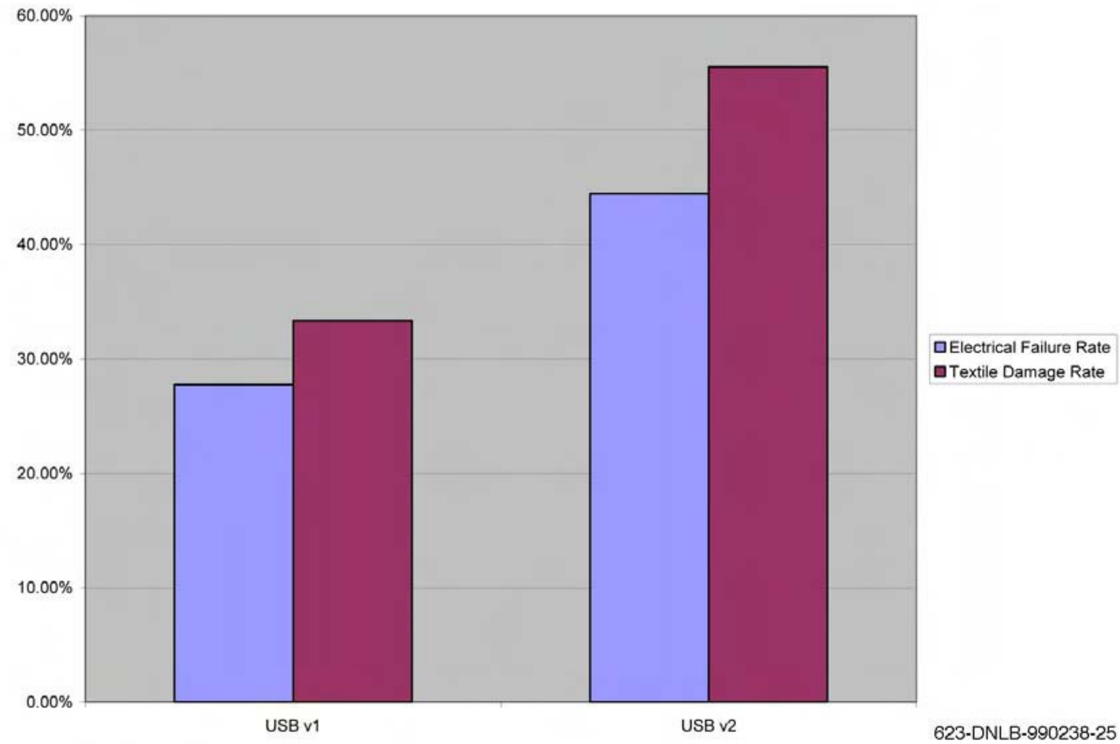

Figure 61. Effect of cable type on failure rate

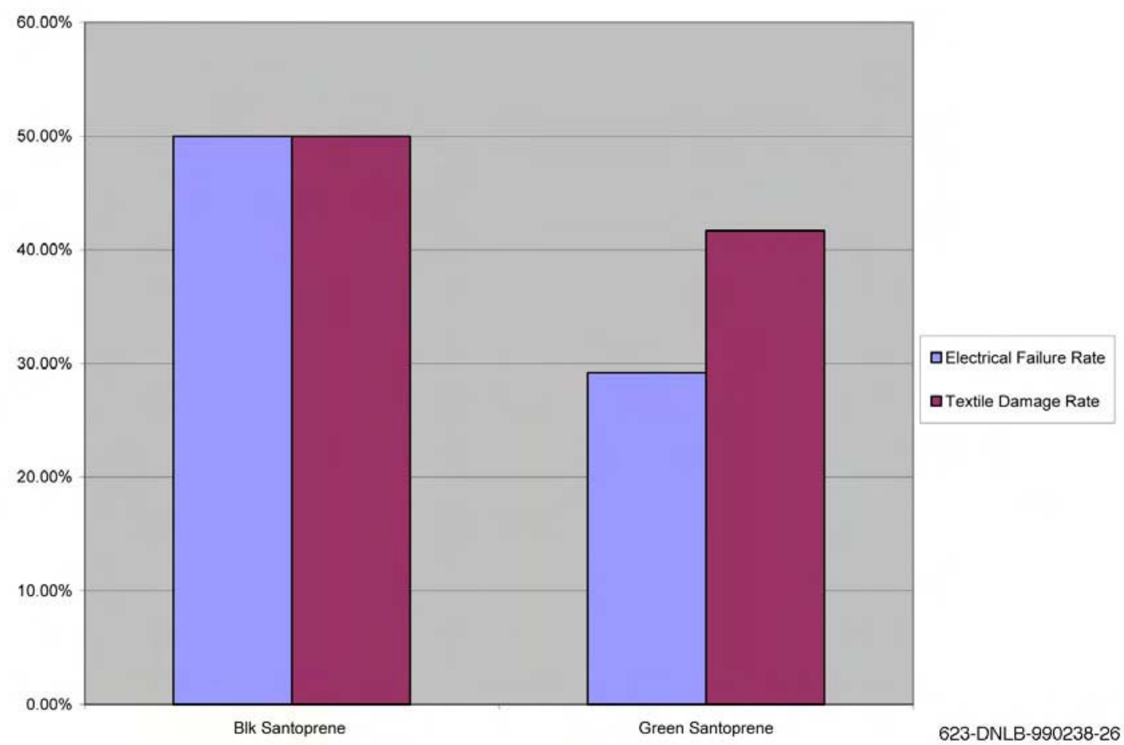

Figure 62. Effect of overmolding material on failure rate

with black Santoprene was relatively small. As a result the trend shown in Figure 62 may be a statistical aberration.

The experimental data was also processed to examine the effects of testing parameters such as the diameter of the impact sphere and the impact energy. As expected, Figure 63 shows an increase in the rate of cable damage with increasing impact energy. Figure 64 shows a pronounced decrease in the rate of cable damage as the cross-sectional area of the spherical impactor is increased. Knowing that the rate of cable damage is proportional to the impact energy and indirectly proportional to the cross-sectional area of the spherical impactor we found it useful to simplify the data found in Figures 63 and 64 by plotting it versus the dimensional group T/A as shown in Figure 65. It can be observed from this graph that the incidences of cable damage are proportional to the Log of T/A.

3.3 Task 3 - Connector and Node Development and Testing

3.3.1 Communications Protocol

3.3.1.1 IEEE 1394

Foster-Miller consulted Boston Optical (BOF), a company specializing in the production of plastic optical fiber (POF), to determine the feasibility of using fiber optics for data transmission. BOF is the U.S. manufacturer of plastic optical fibers and was the supplier of the Phase I fiber

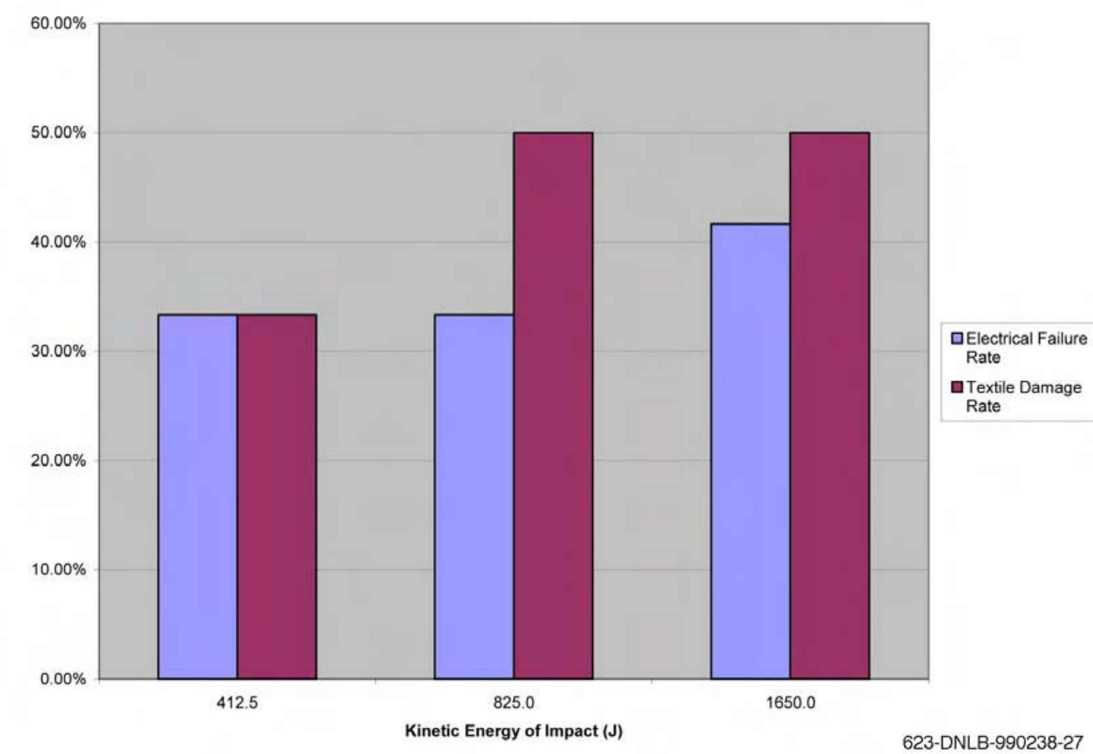

Figure 63. Effect of impact energy on cable failure rate

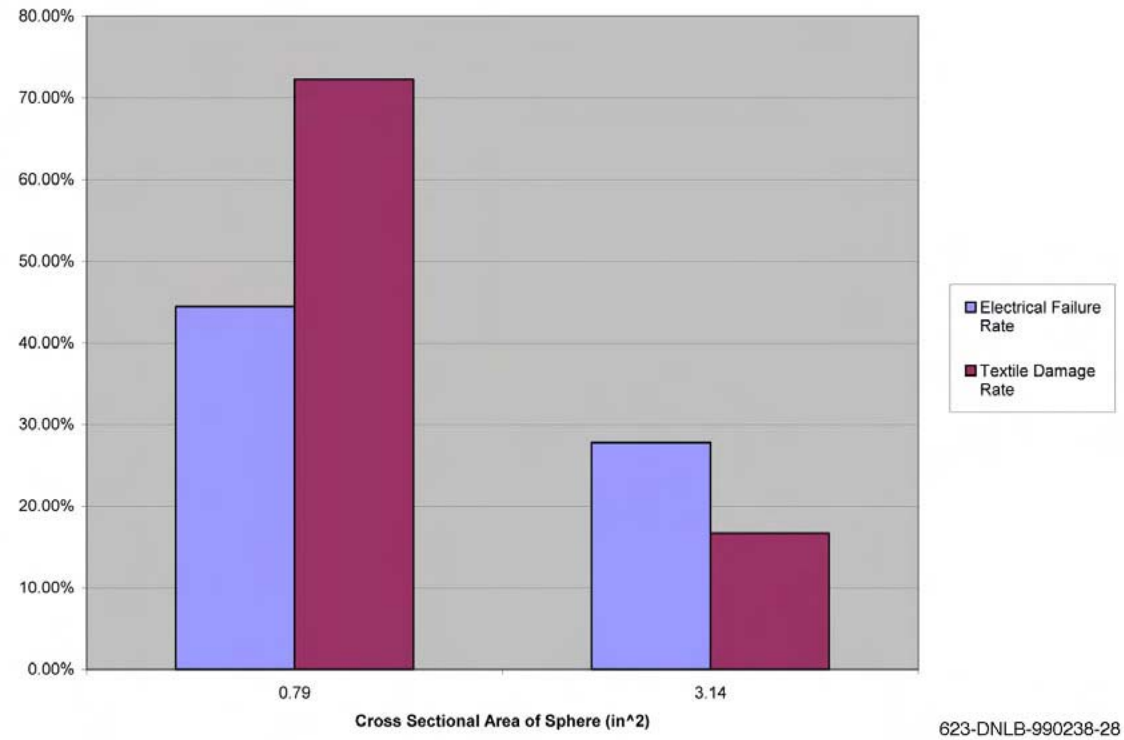

Figure 64. Effect of cross-sectional area of spherical impactor on cable failure rate

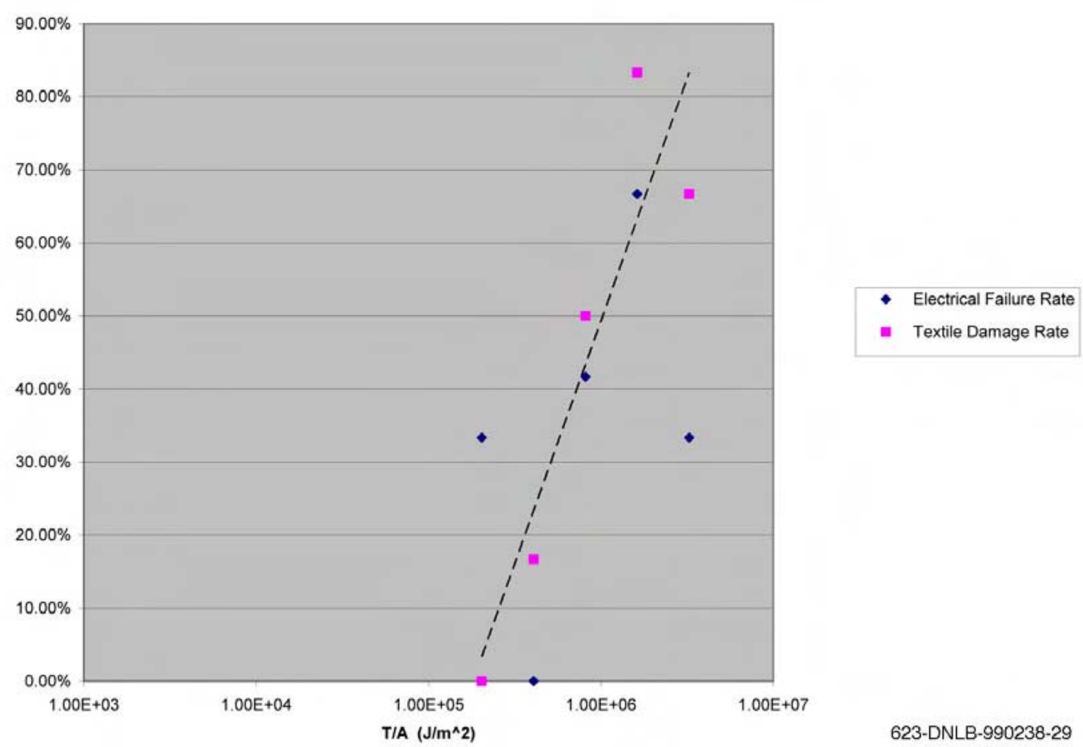

Figure 65. Effect of kinetic energy per unit impactor area on cable failure rate

used in the demonstration webbing. We found that the major hurdle in using POF was the availability of connectors and terminals (electronics).

At the beginning of this program a Japanese consortium was leading the way to design the connectors for Firewire, based around SMI (small multimedia interconnects). BOF had seen some prototypes but the designs were not available at that time. Since that time financial difficulties in the telecommunications sector appear to have halted further development of these connectors. Due to these issues and the poor performance of the braided electro-optic Firewire cable as discussed in subsection 3.2.2.1 the decision was made to not pursue further development of the IEEE-1394 connector.

3.3.1.2 USB 2.0

A USB bus has an A, B or micro-B connector end which plugs into a corresponding A, B or micro-B socket. These connectors are shown in Figure 66. At the request of the Army, we set out to fabricate a connector that could plug into a standard interface. This objective required a modification of the USB 2.0 standard connector shape to accommodate the textile cable, and to allow for the application of as many wearability principles as possible. We chose to keep the USB 2.0 standard connector the same from the point that the plug and socket interface ends. Beyond this, the connector was custom designed to accommodate textile and human factors as much as possible.

To reduce cost and schedule impact, Plastics One requested that we purchase standard USB stamped shell inserts and pins to use instead of building the stamping tools (at least six would be required). We would then connect them to the cable and overmold our shape in place.

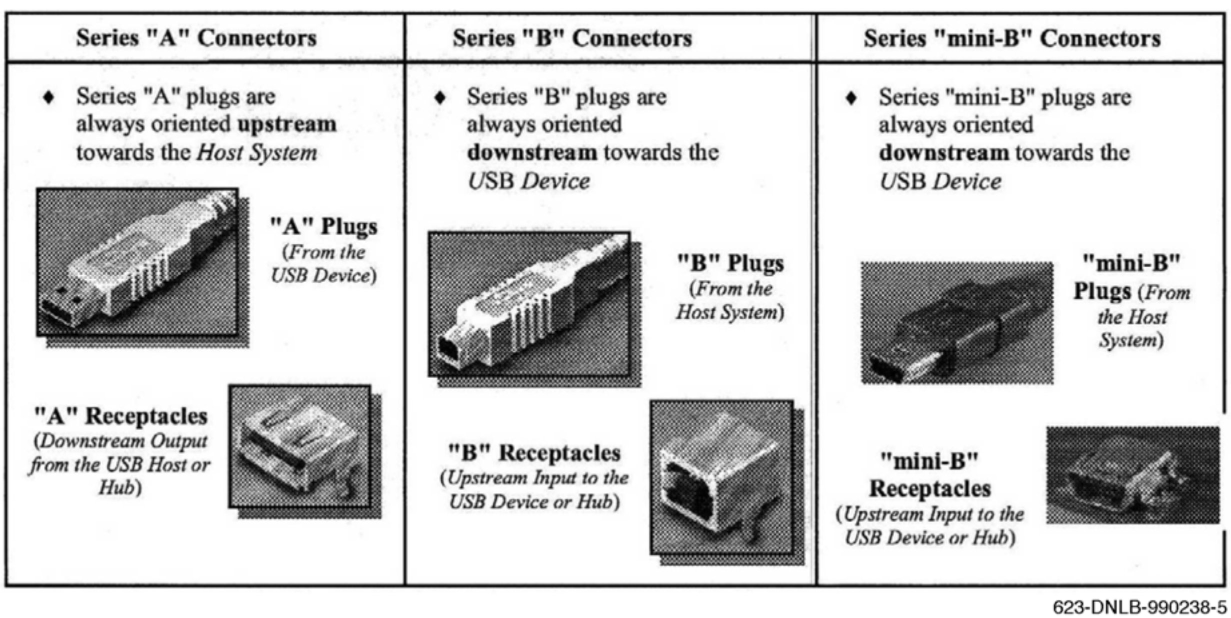

Figure 66. USB connector types

Foster-Miller contacted Panstrong in Taiwan to supply us with the USB A and B shell inserts and pins. Two types of connections to the pins are possible; a crimp connection between the wire and the pin, and a solder connection. Since we had not determined the optimal connection method we chose to purchase both types. Figure 67 shows the USB A and B inserts both assembled (center) and disassembled.

Plastics One and Foster-Miller agreed to use Francine Gemperle along with their own internal design staffs to work on the shape of the overmolding. A thermoplastic hot injection molding technique was selected to produce the final cable connector encapsulation. Since more than one USB cable narrow woven was produced during this program, we decided to make a modular injection molding tool with an interchangeable gate that would allow different cables to be overmolded using the same mold tool, thereby saving cost to the program. The mold would require internal pins to support the textile system and might also require pins or holes to be put into the textile to guarantee bonding between the textile and the injection molded polymer shell.

3.3.2 USB Connector Form Factor Design

Francine Gemperle of CMU visited Foster-Miller to work on the USB connector design onsite. During the working session, we connected the wires of the USB textile bus to the crimp pins and the USB connector inserts for several cables. This assembly is shown in Figure 68. After wrapping the exposed wires and cut textile ends with tape, each cable was overmolded with Sculpty clay to allow us to work on the shapes of the connectors. Special attention was paid

Figure 67. USB connector inserts

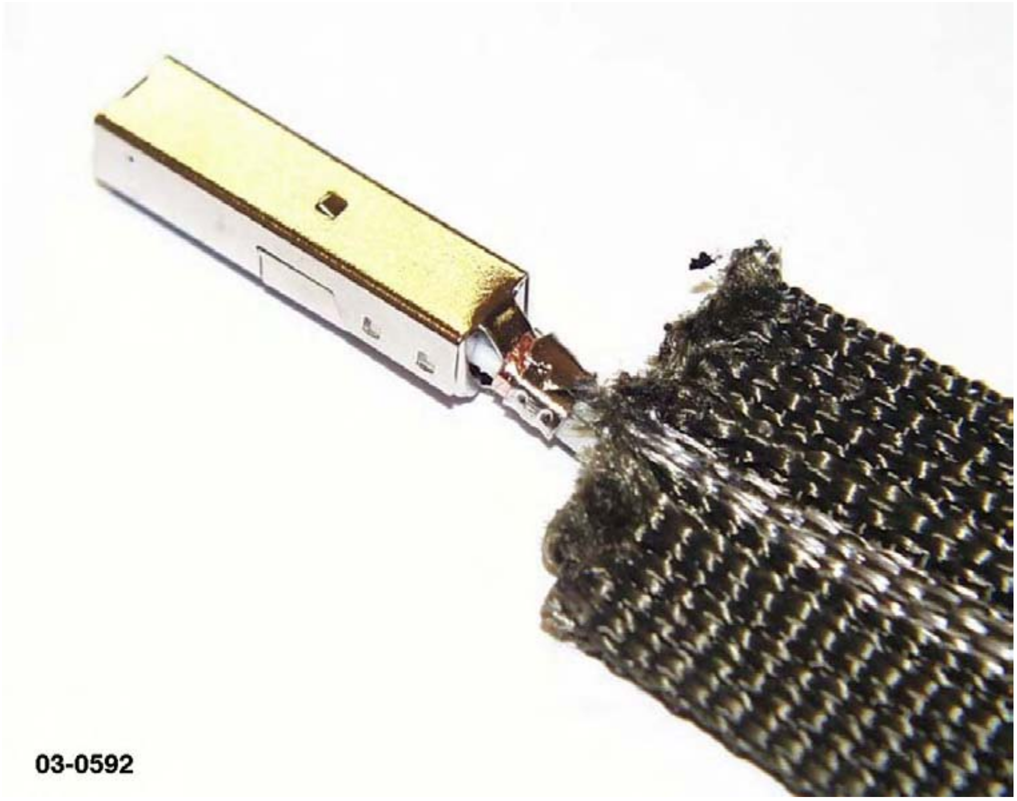

Figure 68. USB connector inserts connected to textile

to the way in which the connector felt in our hand, the rounded edges, contours of the shape, etc. To aid in the design, we had purchased a “pocket USB hub” which was 3 in. x 1.5 in. in length and contained both A and B sockets. The hub allowed us to practice plugging and unplugging the connectors into the sockets when the hub was mounted as a wearable device on our body.

Several shapes were conceived and are shown in Figures 69 to 71. After modifying shapes and working with the informal human factors testing we learned several points about the strain relief, textile connection, and ruggedness.

3.3.2.1 Stabilizing Strain Relief

The shape of the connector must be such that it stabilizes the fragile wires at the point of connection between the textile and the connector, provides strain relief at the point where the housing meets the textile, and accepts the strain for any and all anticipated twisting or motion between a device and the textile. These issues were addressed by placement of plastic bulk and engineered ribbing and the selection of an overmolding material that is semi flexible.

3.3.2.2 Connection to the Textile

The USB connector base should be even with the base of the textile. Some offset space should be incorporated between the connector and the wires in the textile to allow for movement. One possible way to ensure a secure attachment to the textile is to allow the plastic to flow through the gaps between the yarns on the surface of the narrow woven.

Figure 69. Trial shape for USB connector

Figure 70. Trial shape for USB connector

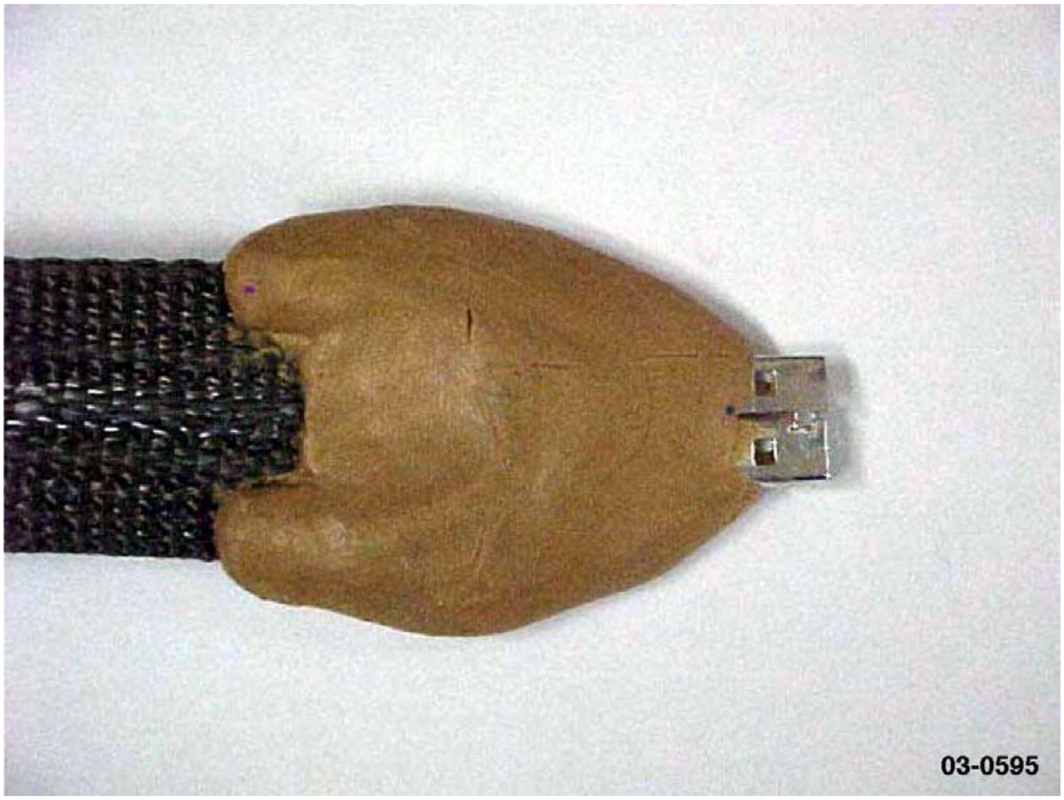

Figure 71. Trial shape for USB connector

3.3.2.3 Ruggedness

The connection/textile interface should be water resistant. The connector also must withstand some level of smashing and dropping. It must withstand steady loading by a human on the order of 400 lb.

3.3.2.4 Interaction, Wearability and Touch

Shape must be such that it fits comfortably and smoothly on the human body. Shape orientation must be easily discernable by touch. Shape must be conducive to the act of plugging and unplugging.

Several sets of conceptual drawings were produced to illustrate different concepts which came from the clay modeling. These drawings (in original form) are shown in Figures 72 to 76. Figure 76 was the preferred connector shape, showing the incorporation of the USB B plug. These drawings were sent to Plastics One for their commentary and inclusion in their designs. Ms. Gemperle was tasked to produce hard models of a preferred concept which would allow better "wearability" analysis, produce CAD drawings of this concept, and communicate with the designers at Plastics One to modify the designs to incorporate manufacturing issues.

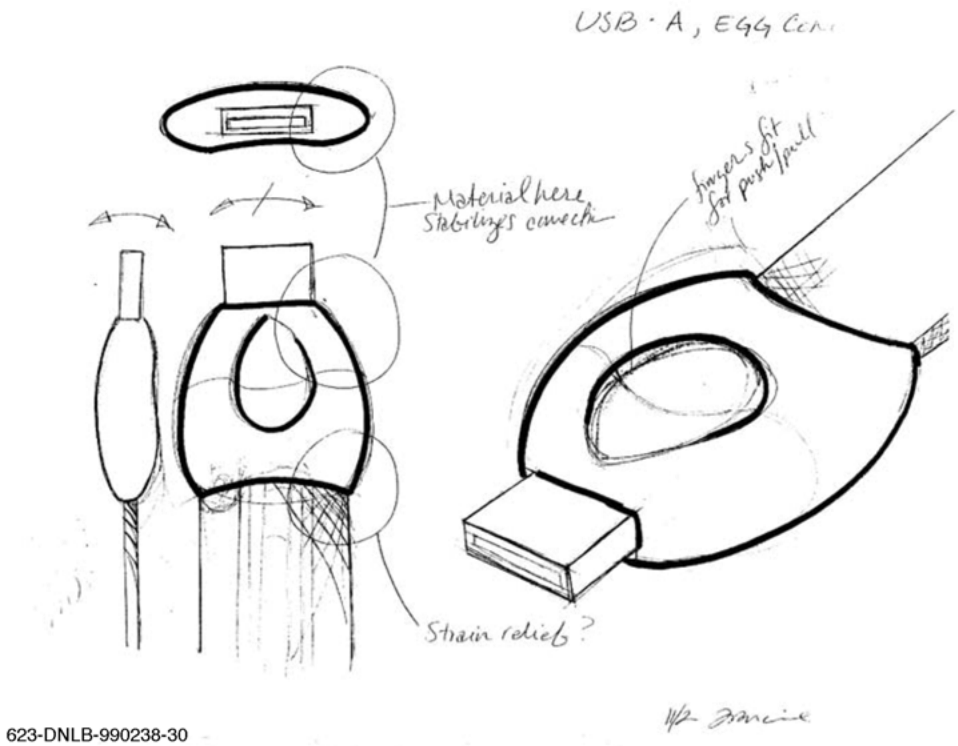

Figure 72. USB Type A connector concept

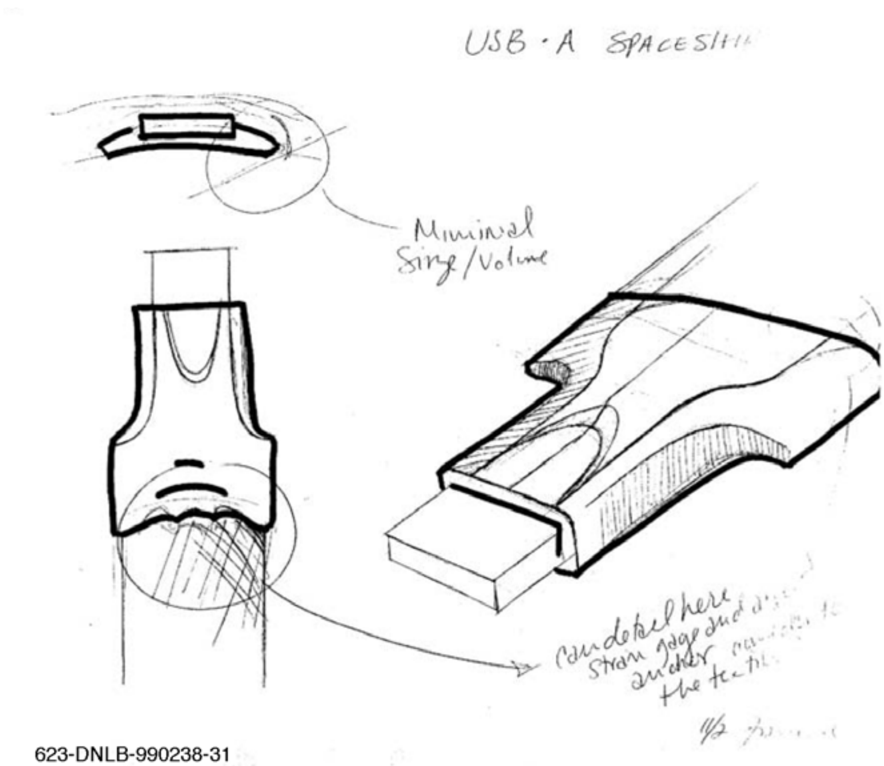

Figure 73. USB Type A connector concept

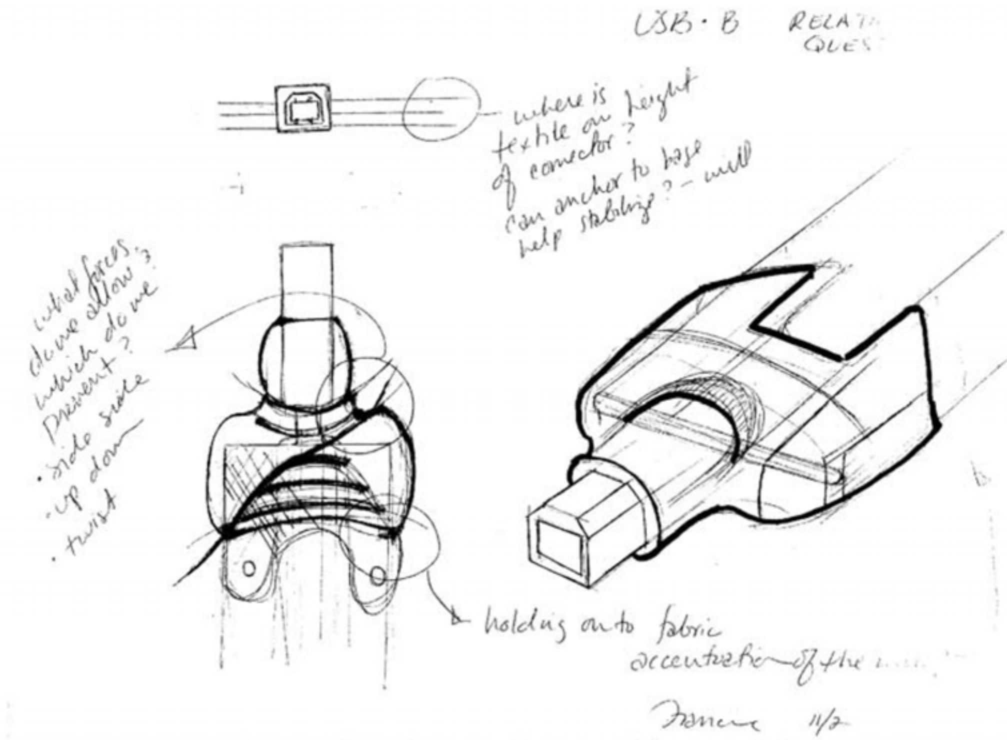

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Figure 74. USB Type B connector concept

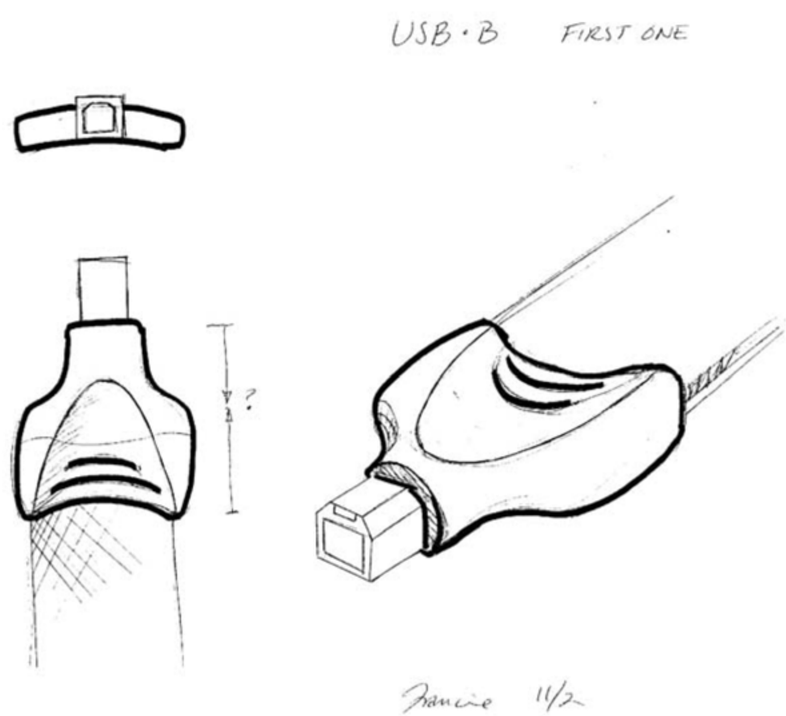

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Figure 75. USB Type B connector concept

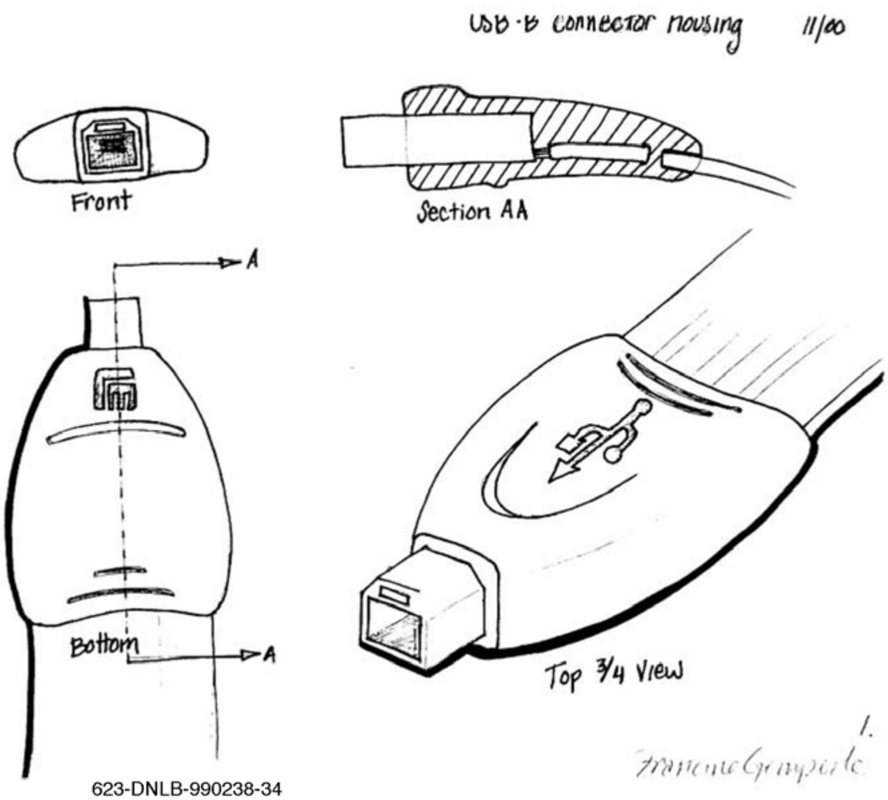

Figure 76. Preferred embodiment of USB Type B connector

3.3.3 Testing and Selection of Connector Material

In the selection process for a polymer to use in the USB connector, three critical factors were identified: processability, durability and comfort. Based on past experience with the Injection Molding process Plastics One selected six polymers, three for toughness and durability and three for comfort. A simple mold was cut to explore the issues involved in injection molding onto a textile structure and samples were made using the six selected polymers (Figures 77 to 82). The relative merits of these polymers were assessed by measuring their hardness or durometer and their pullout strength (Table 15).

The hardness testing of plastics is most commonly measured by the Shore (Durometer) test or Rockwell hardness test. Both methods measure the resistance of plastics toward indentation and provide an empirical hardness value that doesn't correlate well to other properties or fundamental characteristics. Shore Hardness, using either the Shore A or Shore D scale, is the preferred method for rubbers/elastomers and is also commonly used for 'softer' plastics such as polyolefins, fluoropolymers, and vinyls. The Shore A scale is used for 'softer' rubbers while the Shore D scale is used for 'harder' ones. The Shore hardness is measured with an apparatus known as a Durometer and consequently is also known as 'Durometer hardness'. The hardness value is determined by the penetration of the Durometer indenter foot into the sample. Because of the resilience of rubbers and plastics, the indentation reading may change over time, therefore the indentation time is sometimes reported along with the hardness number. The ASTM test

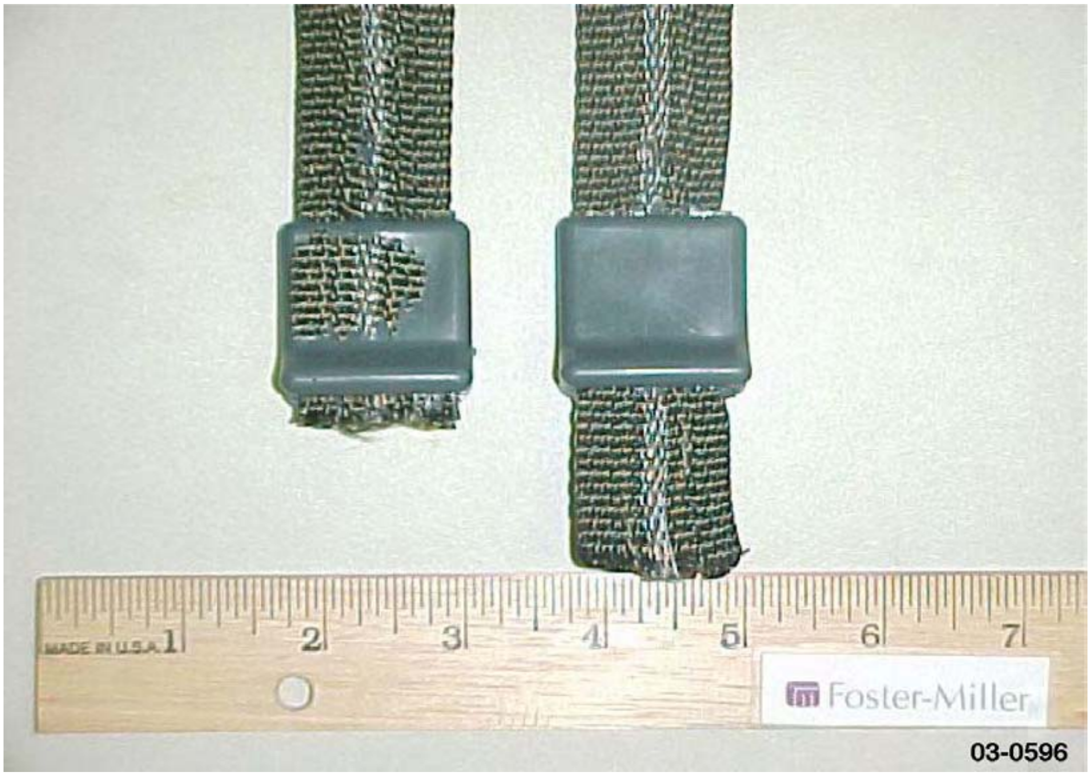

Figure 77. RiteFlex test connector

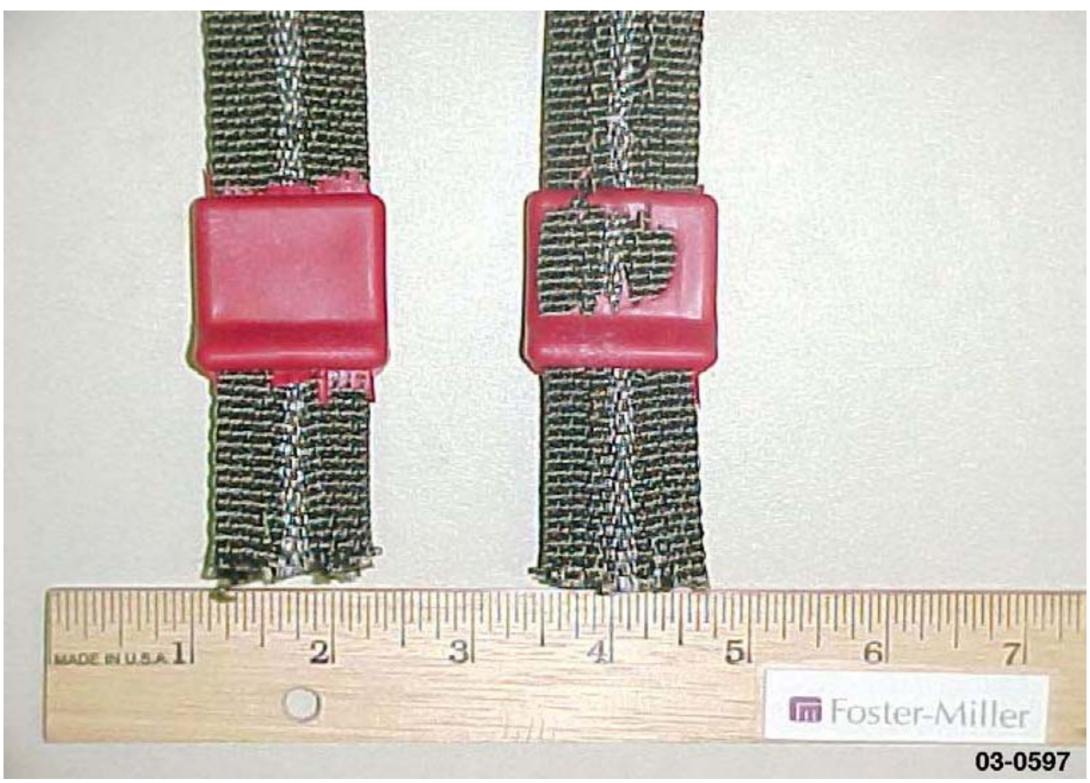

Figure 78. Sarlink test connector

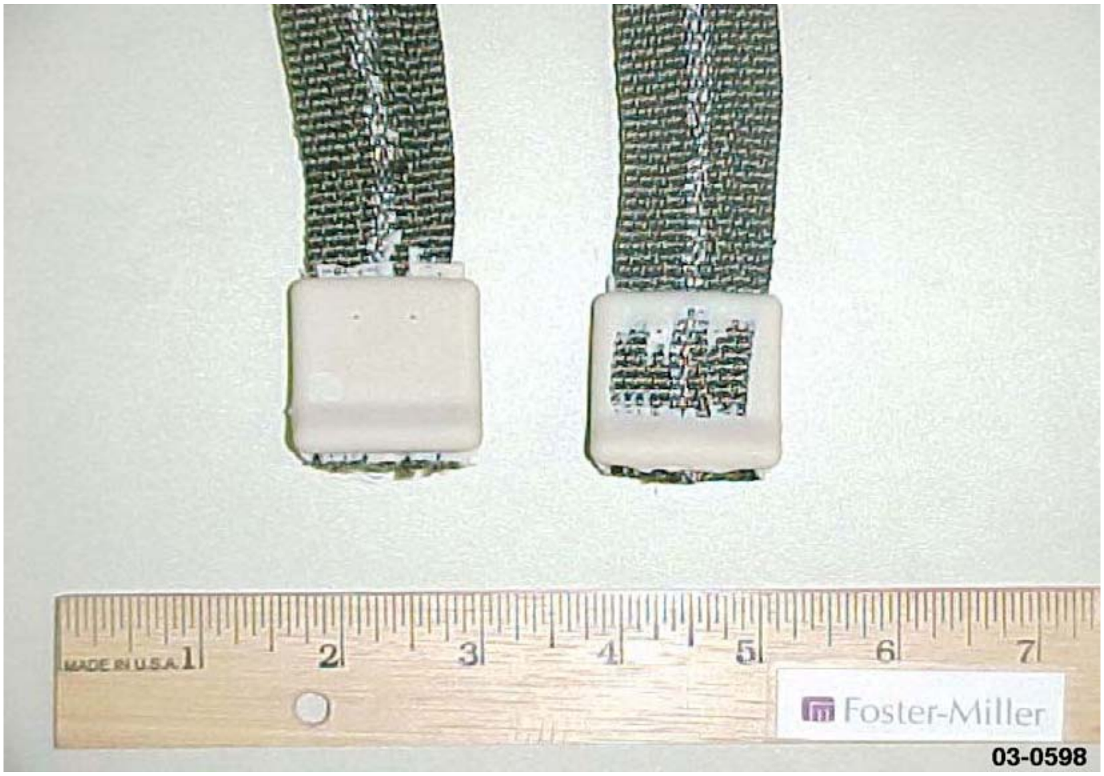

Figure 79. Santoprene test connector

Figure 80. ABS test connector

Figure 81. Nylon test connector

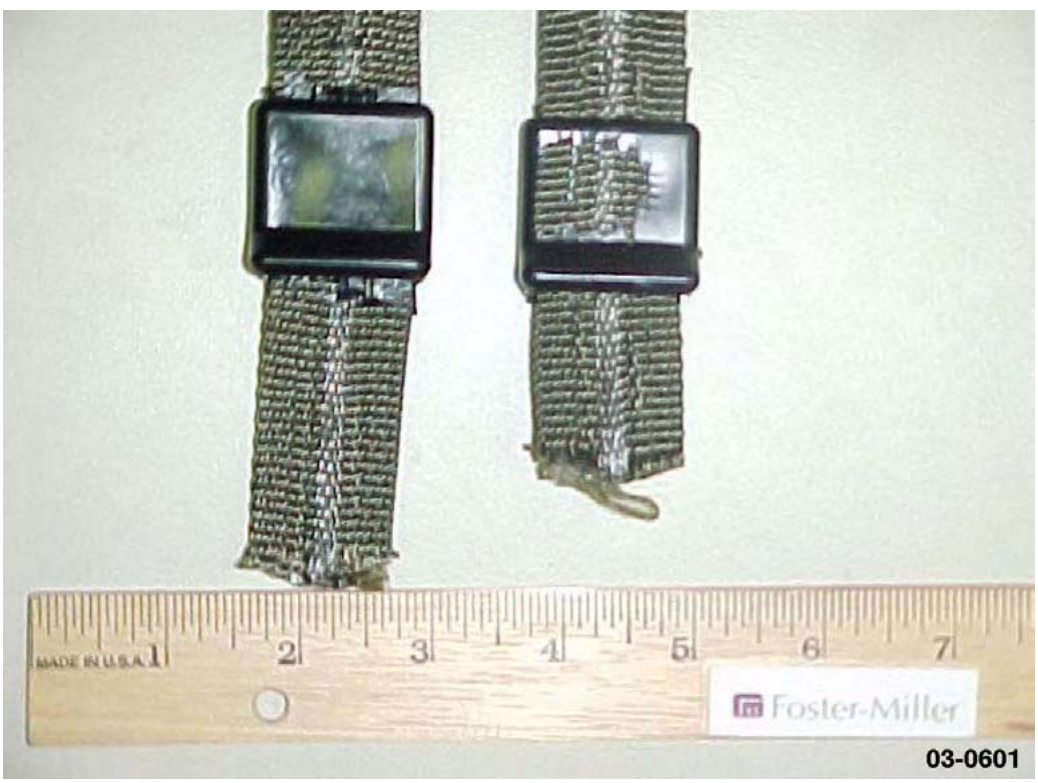

Figure 82. Polypropylene test connector

Table 15. Polymer properties

Material	"Feel"	Pullout Force	Molded Barrel Temperature	Durometer	
				Shore A	Shore D
Rite Flex		>80	365	95	40 to 45
Sarlink	Soft	62	395	95	45
Santoprene		57	430	50 to 55	<10
ABS		>80	435	N/A	75 to 80
Nylon	Rigid	>80	525	N/A	75 to 80
Polypropylene		>80	385	N/A	75 to 80

method designation is ASTM D2240 00. Related methods include ISO 7619 and ISO 868; DIN 53505; and JIS K 6253. The results obtained from this test are a useful measure of relative resistance to indentation of various grades of polymers. However, the Shore Durometer hardness test does not serve well as a predictor of other properties such as strength or resistance to scratches, abrasion, or wear, and should not be used alone for product design specifications.

Due to limitations in Plastics One's test gauge, pullout strengths greater than 80 lb could not be measured. It is evident from the data however that the "soft" class of polymers tends to have an unacceptably low pullout strength.

To accommodate the needs for durability and comfort we decided to make the connector in two parts, a rigid and durable substrate and a soft comfortable overmolding. Nylon was chosen for the substrate due to its mechanical properties and its superior bondability to the Nylon textile cable. Santoprene was chosen for the overmolding as it had the softest feel of the three polymers considered.

3.3.4 Connector Prototype Design and Material Downselect

Based on the competing design requirements of ruggedness and comfort we decided to make the connector in two parts, a rigid and durable premold of Nylon (Figure 83) and a soft comfortable overmolding of Santoprene (Figure 84).

The final connector design was given a rounded form factor and ridges so that it would fit comfortably and securely in the user's hand. Material usage was minimized in the textile end of the connector to provide bend relief. Notches were also incorporated into the Santoprene overmold for the same purpose. The resulting USB connector design (Figure 85) provided comfort and flexibility without sacrificing ruggedness or durability. Based on this design, two stereolithography (SLA) prototypes were made by Plastics One for demonstration purposes (Figure 86). Each cable was terminated with a type "B" connector on one end and type "A" on the other.

Once all concerned parties were convinced of the design's viability, the molds were cut. In creating this mold we tried to solve the problem of excess flash, i.e., molten polymer escaping the mold cavity. The flash issue was found to be caused by the use of rigid mold inserts which were unable to clamp down with sufficient force to block all the inter-yarn channels on the

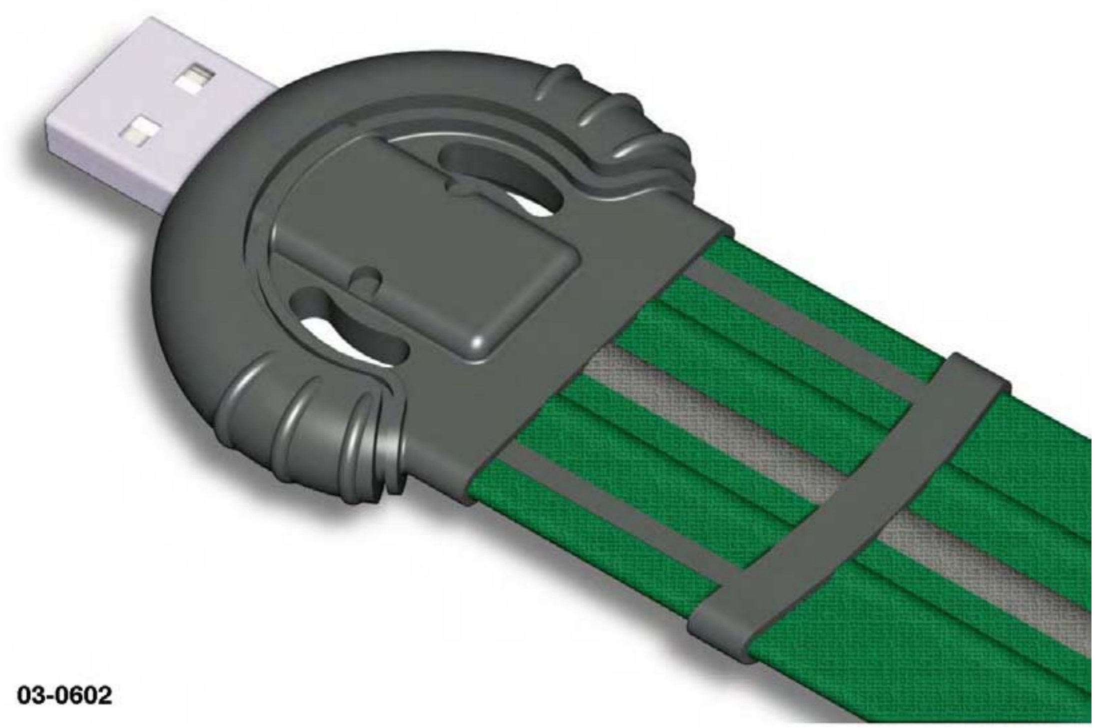

Figure 83. Proposed USB nylon premold

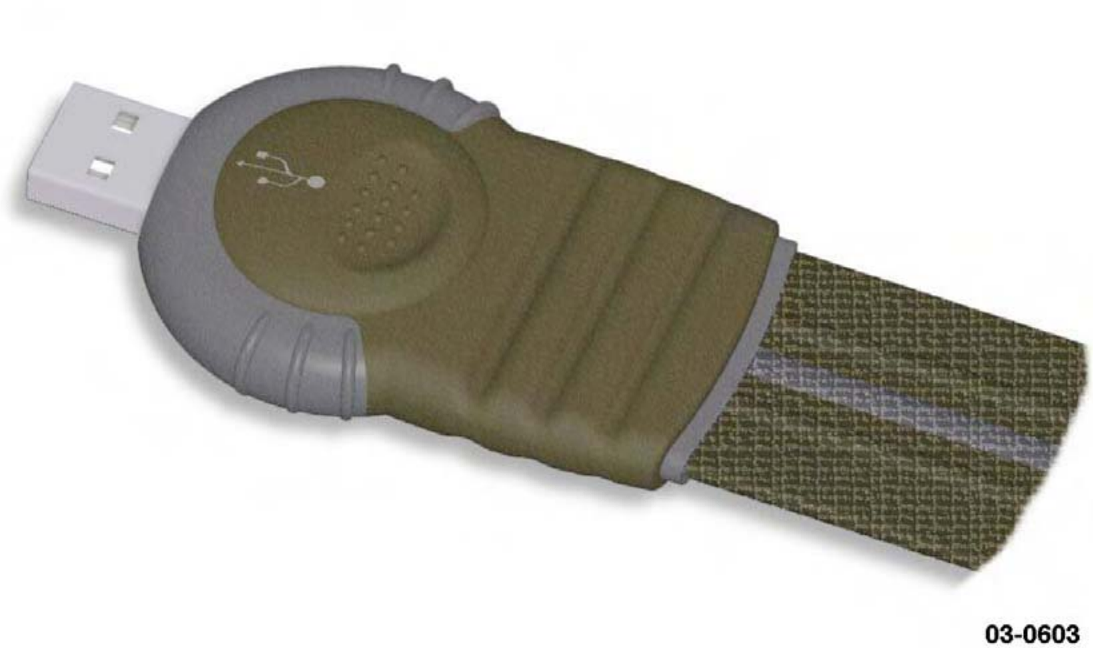

Figure 84. Proposed USB Santoprene overmold

Figure 85. Proposed USB connector design

Figure 86. USB v1 cable with SLA connector

surface of the textile cable. A solution to this problem was found by using malleable mold inserts that were capable of deforming under pressure, closing off these channels.

The procedure used to fabricate the cable assembly and the USB connector overmold was as follows:

1. Fabrication of cable assembly.
   - Strip wires.
   - Install Teflon® tubing on each lead.
   - Solder to connector.
   - Trim metal shell.
   - Install into metal shell.
   - Solder drain wire to shell.
2. Pot completed cord w/epoxy (or equivalent).
3. Overmold with nylon premold.
4. Test.
5. Overmold with Santoprene.
6. Final Inspection.

Initial parts were fabricated and molded "as is" to give us a baseline process. No potting or special techniques were used. Basically this run provided strip lengths for the future detailed process. The failure rate of this initial baseline run was over 90 percent. Analysis of parts that were cut open found that the reason for this failure was shorting, due to the melt temperature difference between nylon (520°F) and the PVC wire jacket (typically in the mid-300's). During molding the PVC reflowed and allowed bare conductors to short against the metal connector housing as shown in Figure 87.

Subsequent prototypes were built using an epoxy or similar material to pot the cavity (Figures 88a and 88b). Teflon® tubing was also slipped over the individual leads to prevent shorting (Figure 89). Although labor intensive, this combination reduced the failure rate to under 10 percent. The first and second group of cables shipped were built using this technique.

Using this assembly process, 35 connectorized cables were then produced in 0.5m, 1.0m, 2.0m, 2.5m, 3.0m, 4.0m and 5.0m lengths; 5 cables per length. These specimens were sent to Contech Research for signal integrity testing, which was passed. While this initial connector was found to be electrically functional several mechanical design issues were observed. These preliminary mold runs showed problems with cracking around the USB plug, and movement of the cable within the mold as shown in Figures 90 and 91, respectively.

3.3.4.1 Water Resistance Testing of USB Overmold

Three sets of USB v1 cables, connectorized on both ends, were tested to asses the resistance of the USB overmold. Of particular concern was the possibility that fluids might wick up the textile due to capillary pressure and short the connector. To test this possibility the three cables were submerged in a solution of water and black clothing dye for 12, 24 and 48 hr, respectively.

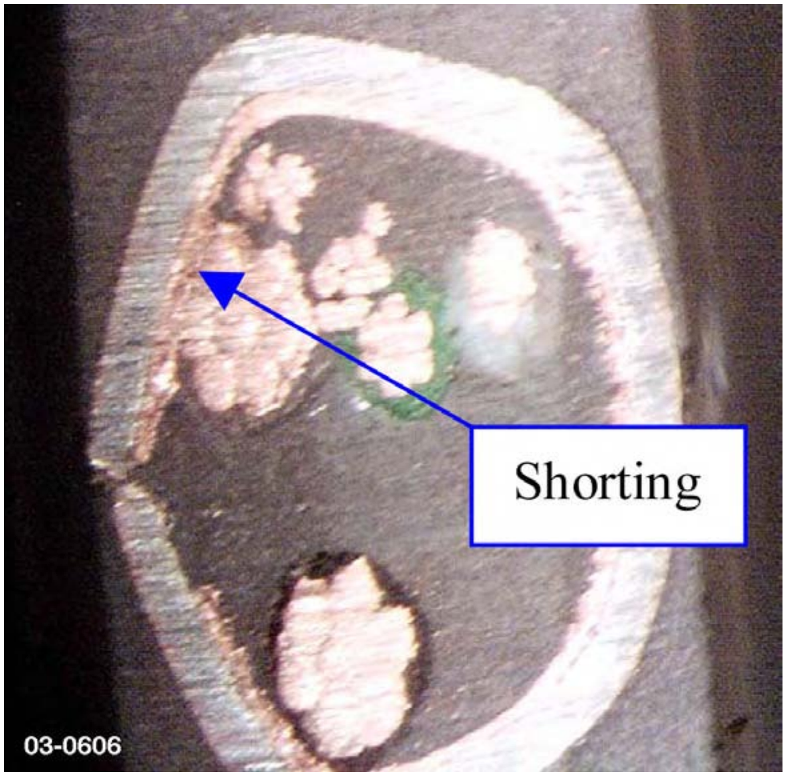

Figure 87. Shorting between power wire and metal housing

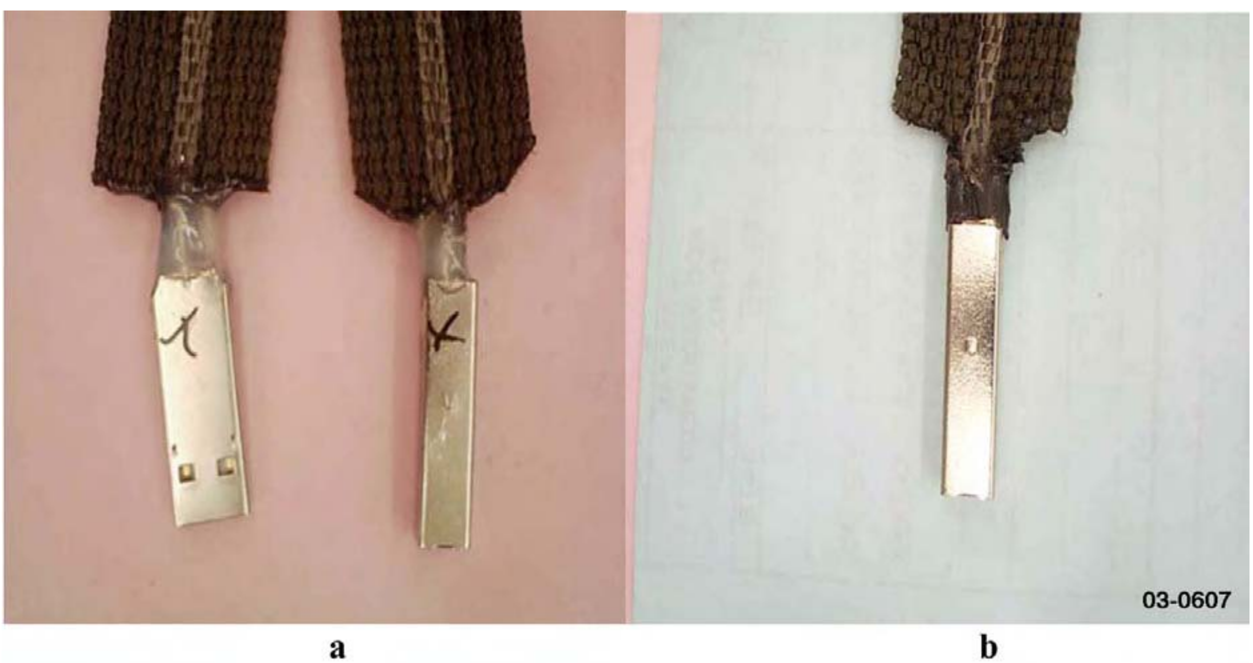

Figure 88. Potting using a) epoxy and b) "Riteflex"

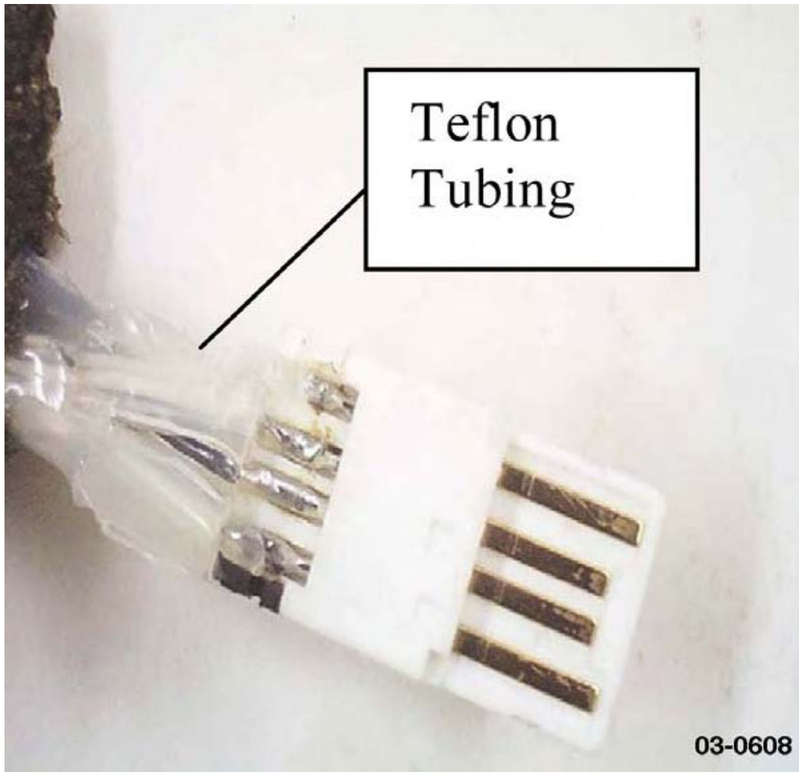

Figure 89. Subassembly with protective Teflon® tubing

Figure 90. Cracking near USB plug

Figure 91. Poor wet-out of textile due to cable migration during injection molding

The specimens were allowed to dry and then cut open and inspected for signs of wicking. It was found that even after 48 hr, the clothing dye and water solution had not made any progress into the overmold.

3.3.5 Refining Connector Design

A concern that arose after inspecting the first batch of USB connectors was that the bend relief was inadequate. The connector design was intended to allow flexibility through the use of narrow ribs in the premold and groves in the overmold. In an effort to provide a rugged, wear resistant overmolding, however, a grade of Santoprene was selected that had a relatively high durometer. This material had the effect of making the entire assembly undesirably stiff. After discussions with Plastics One we decided to try several test runs using different durometers of Santoprene. In order to prevent textile show through in this sample run, the individual conductors in the USB v1 bus were artificially straightened using pliers. This procedure was done to remove the significant waviness in the textile and provide a more uniform geometry in the mold. The results of these trials can be seen in Figures 92a-b. It is obvious from these pictures that the problem of textile show through had not been solved and had little to do with waves or bumps in the conductors.

To address the issue of textile showing through the connector, twelve guide pins were added to the mold to hold the cable in place during mold injection. It was also decided at this time to use the Santoprene with a Shore A durometer of 73. This grade of Santoprene was felt to provide the best tradeoff between durability and bend relief. These modifications to the USB mold design

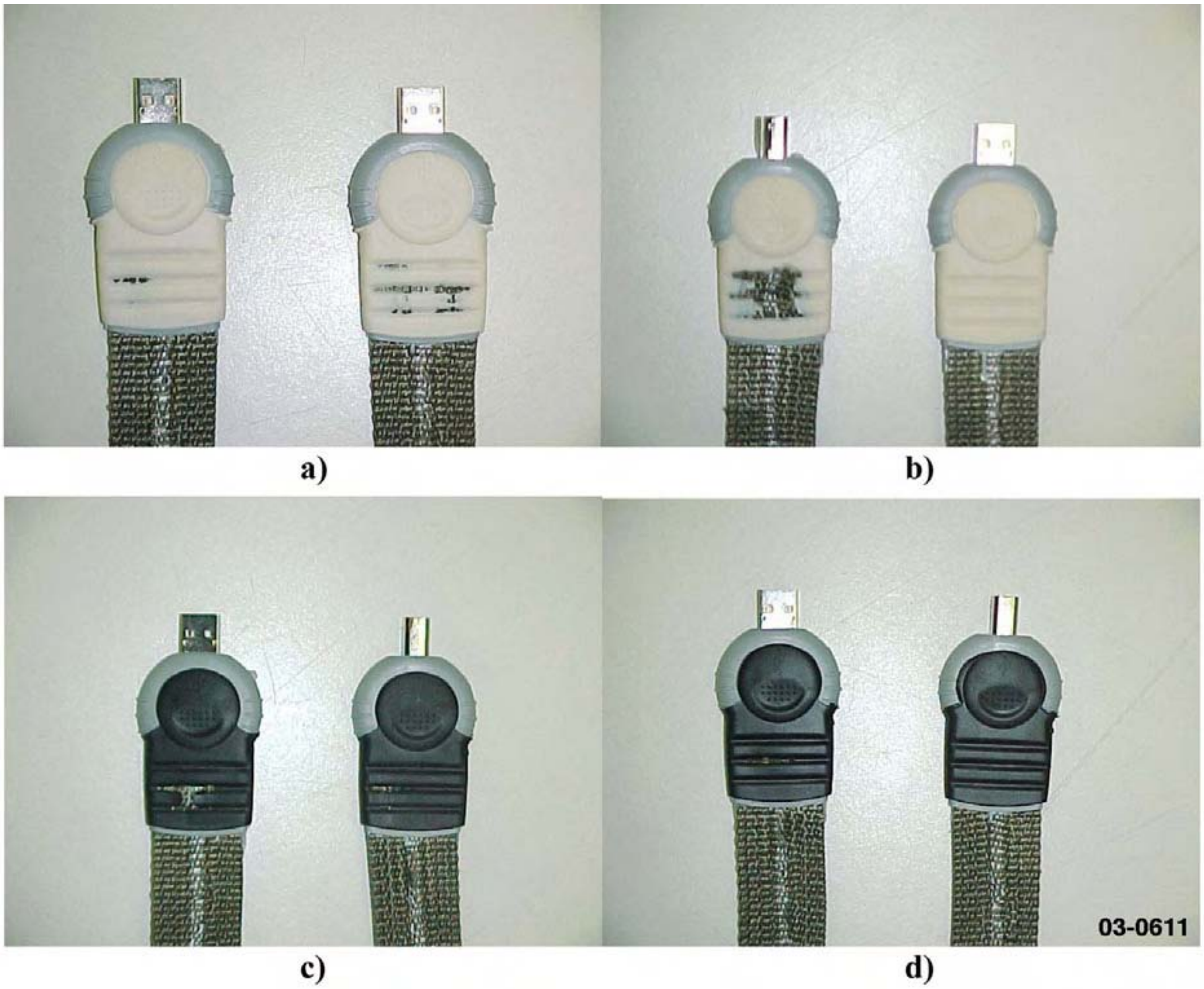

Figure 92. USB connectors with Santoprene overmoldings having a durometer (hardness) of a) Shore A 55, b) Shore A 64, c) Shore A 73, d) Shore B 40

were found to be effective and the results can be seen in Figure 93. All cables fabricated using this refined designed were found to have a more comfortable feel, improved bend relief, and be free of textile show through.

In addition to these design changes several process improvements were tested. A simple potting mold was created for both the USB type A and B connectors. Initial parts were molded on 16 September 2002 and test fit in the premold. Since clearance was adequate, we decided to open the mold an additional 0.030 per side to improve material flow over the wires, as well as to increase the thickness of the “potting layer.”

After sampling the premold on several parts, however, the technique was abandoned. It was found the internal premold design required too much material to be stripped off the wires, resulting in a thin “neck.” During injection the wires all washed to one side (in part due to the flexibility of the individual wires), resulting in incomplete fill on one side of the assembly, which defeated its purpose (to protect the wires from nylon when the external premold was being

Figure 93. New overmold using guide pins and softer Santoprene

molded). As a result, the third and final group of cables was molded using epoxy as the potting material.

3.3.5.1 Recommendations

It should be noted that the complexity of the process details discussed above are due primarily to the nylon premold. The USB connector and wiring were both designed for overmolding with a lower temperature PVC, Santoprene, or polyester-based materials, and when used with such materials would not require special techniques discussed, nor would it exhibit the high failure rate. Nylon was chosen for the benefits it provided (strength) and the process had to accommodate the challenges it raised. We felt that further exploration of the use of a monolithic single stage overmold was appropriate. To that end a process improvement test was performed at the end of the program that eliminated the nylon premold and overmolded five replicates with Riteflex (Figure 94). Since the mold was not designed for this use, some textile showthrough and flashing were observed. These artifacts are easily corrected in a dedicated mold and are not a primary concern. Inspection of these overmolds showed a promising compromise between bend relief, ruggedness and economy of fabrication effort.

Based on observation made by Foster-Miller and Plastics One throughout this task the following actions are recommended:

1. While the premold/overmold concept worked well, it is labor intensive. Future work should investigate monolithic mold designs.

Figure 94. Single stage Riteflex overmolded part

2. When selecting an overmolding material, care should be taken that its injection temperature does not exceed that of the wiring insulation or shorting may occur. If this option is not feasible, it should be insured that the molding material does not come in contact with any exposed wires. Prepotting or premolding the wires with a lower temp barrier material are effective ways of protecting the wires.

3. An adequate number of positioning pins should be included at the outset of mold design to prevent cable washout and textile show-through. In the Phase II USB design a third set of pins should be used between the two existing rows.

3.4 Task 4 – Non-Connected Interface Development and Testing

3.4.1 Investigation of Wireless Power/Data Transmission Technologies

The requirements of data transmission and power transmission are complementary. For data transmission, bandwidth is the most important characteristic. Bandwidth has several benefits for the warrior application, some of which are not immediately apparent. High bandwidth links can eliminate expensive and power hungry data compression, and minimize the number of transmission lines needed to implement various functions. Examples of low bandwidth channels for transmission of body sensor data abound in recent biomedical applications. In these applications a high bandwidth transmission channel removes many of the limits on the number of sensors that can be handled in a biomedical data acquisition system.

The most important issue for power transmission from a soldier system standpoint is efficiency. The overall power budget of wearable electronics has become the sum of many small power drains plus a few larger ones from central computers, night vision goggles and radio transmit/receive gear. The overall system efficiency in the military wearable electronic system is achieved by both improving energy efficiency of the various elements of the system and by utilizing these system components only when needed. Making the transmission of even small amounts of power as efficient as possible is therefore important.

The issues of emissions, textile compatibility, and connectivity are well understood and are more related to implementation than basic requirements. The idea of connectivity is particularly important for system architecture. Telemetry for instance has the largest connectivity with two-way connection to any other telemetry site on the clothing. This extra connectivity is limited practically only by the bandwidth of the telemetry transmitter/receiver channel.

A series of meetings were held at Foster Miller to investigate the problem of transmitting power and data across non-connected interfaces in the soldier ensemble. The most promising technologies were identified and are discussed below:

Telemetry

Data transmission can be achieved with telemetry across boundaries using RF chips with small built-in antennas. The power required in the actual electromagnetic wave to carry the data to the receiver is in the sub-microwatt range. The signal levels must be raised, however, to the levels required by the data transmission system before being injected into the transmission line on the other side of the textile boundary. Systems such as these are commonly used to transmit data from Physiological Status Monitoring (PSM) sensors to a central computer for processing.

Capacitive

Capacitive coupling can be used to transfer power across a boundary as indicated in Figure 95. In narrow bandwidth applications a capacitive coupling results in an efficient energy transmission system. Alternating current is required for energy transfer when using capacitive coupling. This system is similar in principle to an inductive or transformer system.

The basic elements of a capacitive power transmission system are:

- *Converters:* converts RF to DC.
- *Oscillators:* converts DC to RF.
- Matching inductors.
- Conducting capacitor plates on the surface of the boundary, i.e., the fabric.

The function of the first two of these components is discussed in detail below in the discussion of transformer coupling. The implementation is less intrusive than the implementation of a transformer in a textile environment. The capacitor plates can be made with textile friendly materials such as metallized organza or a woven screen of conducting threads, e.g. tinsel wire.

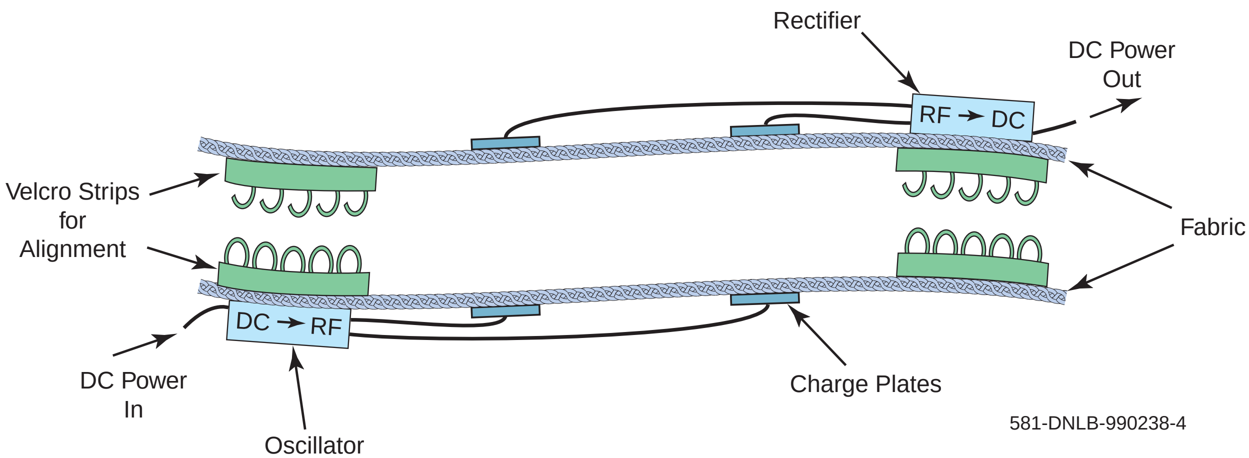

Figure 95. Capacitive coupling concept

The problem with capacitive coupling rests in the difficulty of creating the inductance needed to resonate the circuit.

Optical/Infrared

The system efficiency of optical power transmission system is too low to be of interest for a warrior application. Optical data transmission, however, appears more promising. The essential components of an optical data transmission system between two wire transmission lines implemented in a textile context are shown in Figure 96. The basic optical elements are a diode emitter (or diode laser) for transmission and an unbiased diode on the receiver side of the boundary. Two sets of optical components are needed to implement a two-way system. The receiver diode has to be large enough to allow for lateral motion. An unbiased diode (called a solar cell in the optical region of the spectrum) is shown in Figure 96. The actual size of the receiver depends on how much motion is allowed between the garments.

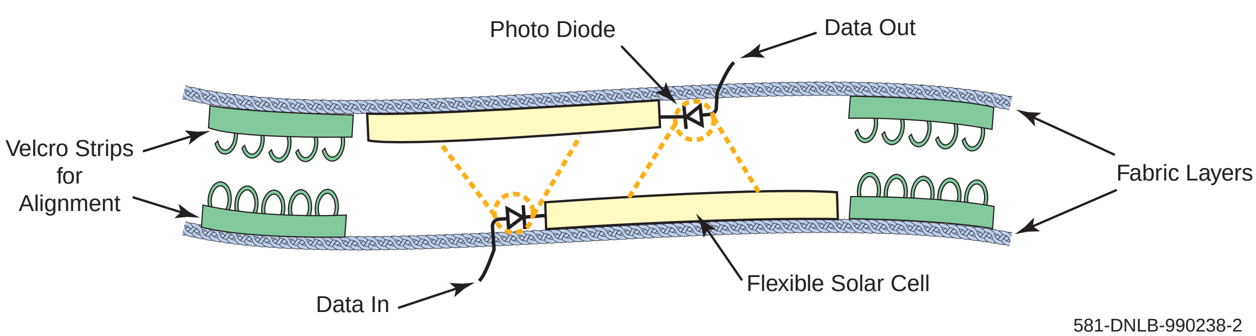

Figure 96. Optical infrared transmission concept

The type of conditioning circuits needed in conjunction with the photo diodes depends on the type of transmission line that is coupled. For wire transmission lines the basic transmit /receive photodiode configuration is needed. The photodiodes are low voltage devices so that current to voltage circuits are required on receive side of the system and voltage to current conversion circuits on the on the transmit side of the system. The data bandwidth in this case is restricted to less than 1 MHz.

High data rates can be achieved if optical fiber transmission lines are used. Only transmit diodes are needed because they directly feed the optical fiber on the other side of the cloth boundary. To achieve a high data rate transmission, the transmit diodes must be back-biased with a DC voltage. All of the required components could be implemented in a flex circuit with surface mount components.

Air Core Transformers

Air core transformers consist of primary and secondary conductive windings in close proximity (Figure 97). Leakage reactances are ordinarily high in these systems. As a result the coefficient of coupling between the primary and secondary windings tends to be low. Thus the voltage induced in the secondary winding depends on the mutual inductance of the two windings. The use of at least one circuit in place of a pair of simple reactances reduces efficiency losses.

Table 16 outlines the key results of a trade study performed between the various candidate technologies. Besides the performance characteristics listed, one other important issue is reliability. Reliability is difficult to quantify and may require the development of packaging solutions to protect the signal channel under operational conditions.

Given the different requirements for transmitting power versus data, we decided that these issues should be tackled separately. Initial trials at Foster-Miller concentrated only on power

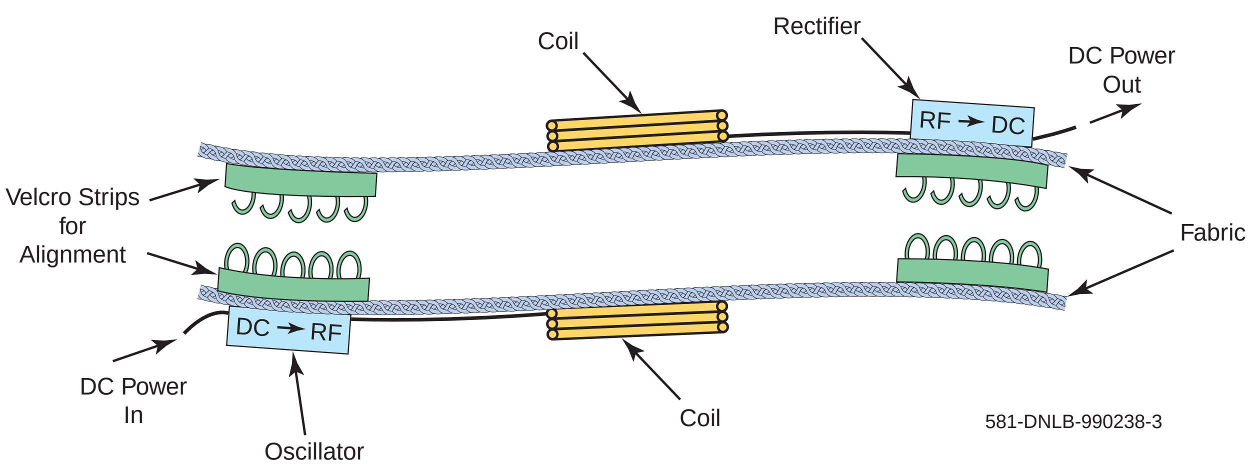

Figure 97. Transformer transmission concept

Table 16. Methods for coupling data and/or power across textile boundaries

	Bandwidth	Efficiency	Emissions	Wearability
Telemetry	10 MHz	>1%	Very low	Good
Transformer	1 MHz	~80%	Low	Excellent
Capacitive Inductance	1 MHz	~80%	Low	Good
Optical/ Infrared	1 GHz	~10%	Negligible	Good

transfer since providing for data transfer at the same time, although possible, becomes more difficult from a software/analysis standpoint. Due to their relatively high efficiency and superior textile compatibility, air core transformers were selected for further investigation as a means of transmitting power.

3.4.2 Testing and Evaluation of Air Core Transformers for Power Transmission

Throughout this effort the following issues were investigated:

- Effect of number of turns of wire comprising the coils.
- Effect of misalignment of the coupling coils.
- Effect of wire type.
- Effect of loop diameter.

3.4.2.1 Trial 1

In this initial trial a set of coils made from 2 overlapping turns of tinsel wire was constructed and manually sewn to swatches of BDU fabric representing the two layers of the envisioned fabric system interface, i.e., shirt and undershirt. Tinsel wire was chosen due to its textile compatibility and its demonstrated use in electrotextile structure such as the radiator in the Merrenda antenna (No. DAAD16-99-C-1047). We decided to make the coil diameter approximately 2-1/2 in. as a starting point to evaluate the efficiency of the system. This size was felt to strike a reasonable balance between the competing desires for large loops for improved efficiency and small loops for better wearability. The impedance of these loops was first measured on a HP Network Analyzer (Figure 98). An example of the Smith plots obtained for one of the tinsel wire coils is shown in Figure 99, and the complete data for both coils is presented in Tables 17 and 18.

The pair of coils was placed face to face to form an air core transformer. This transformer was characterized in the 1 to 10 MHz range using the Network Analyzer.

The efficiency of the power transfer (e) from one of the coils (called the primary) to the second coil (called the secondary) was then determined. This calculation can be performed two ways. The first is to directly measure the transfer coefficient and the second is to calculate it using the measured value of the reflection coefficient (ρ) in the following equation:

$$eff = 100^* (1 = \rho)$$

Figure 98. HP network analyzer

The difference between the measured and calculated values of transfer efficiency can be used to determine the losses in the transmission line if the system is properly tuned. Transfer efficiency achieved in the above coupling was extremely low. Figure 100 shows the transmission coefficient (t) across the 50 KHz to 10 MHz frequency range. Knowing the transmission coefficient, the transmission efficiency can be determined at a particular frequency using the formula:

$$\text{eff} = 100 * \left[10^{\left(\frac{t}{20}\right)} \right]$$

We determined the best transfer efficiency occurred near 10 MHz. At this frequency the transfer efficiency was approximately 0.01 percent. The reason for such poor performance is that the impedance of the network analyzer and the transformer coils were not matched, resulting in most of the signal being reflected rather than transmitted. For optimum transmission efficiency the characteristic impedance of the transmission line and the impedance of the load and the source should all be equal. In this case the source (the transformer coils) has a relatively small impedance while the load (network analyzer) has a 50Ω impedance. To correct this discrepancy a 50Ω resistor was placed across the secondary coil. This action resulted in a ~2 percent improvement in transfer efficiency.

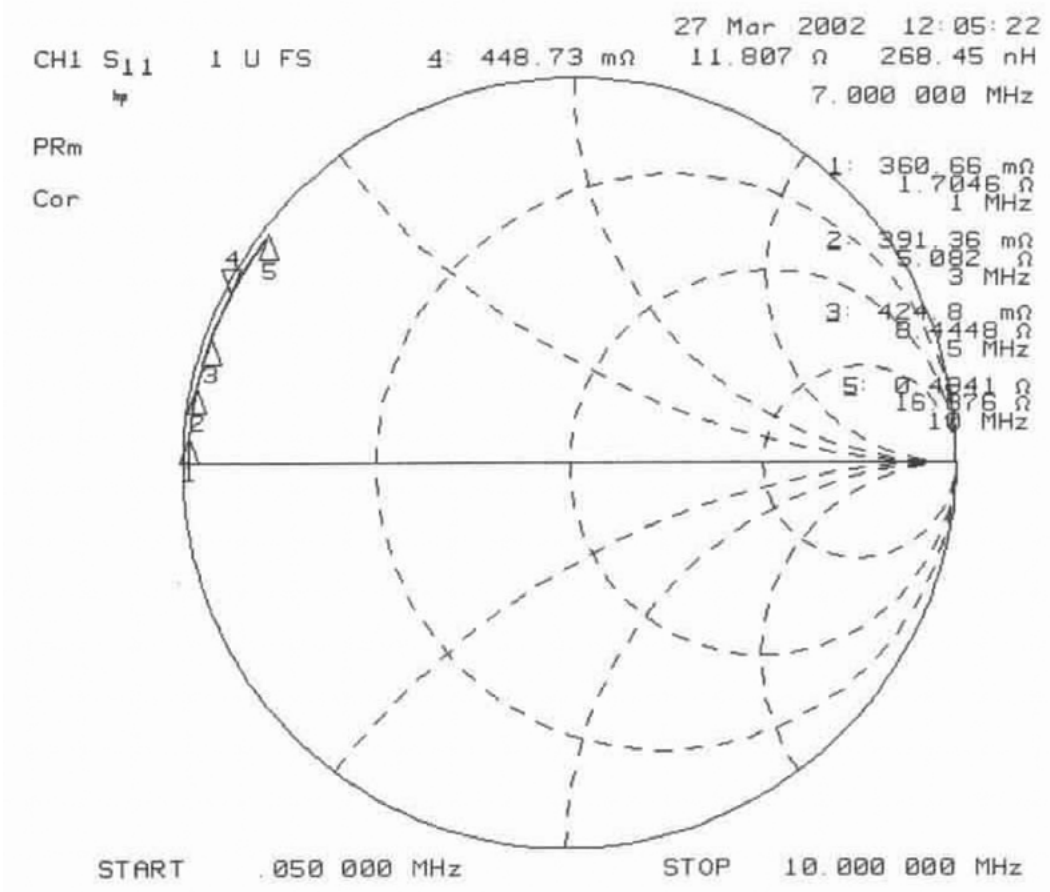

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Figure 99. Smith chart plot used to determine coil impedance across desired frequency range

Table 17. Effects of frequency on loop impedance for tinsel wire coil No. 1

2 Turn Tinsel Wire. Coil No. 1 (on Fabric)	Resistance (Ω)	Reactance (Ω)	Impedance (Ω)
1 MHz	0.60	1.95	0.60 + 1.95i
3 MHz	0.79	5.74	0.79 + 5.74i
5 MHz	1.06	9.43	1.06 + 9.43i
7 MHz	1.39	13.02	1.39 + 13.02i
10 MHz	1.88	18.24	1.88 + 18.24i

Table 18. Effects of frequency on loop impedance for tinsel wire coil No. 2

2 Turn Tinsel Wire. Coil No. 2 (on Fabric)	Resistance (Ω)	Reactance (Ω)	Impedance (Ω)
1 MHz	0.36	1.7	0.36 + 1.7i
3 MHz	0.39	5.1	0.39 + 5.1i
5 MHz	0.42	8.4	0.42 + 8.4i
7 MHz	0.45	11.8	0.45 + 11.8i
10 MHz	0.49	16.9	0.49 + 16.9i

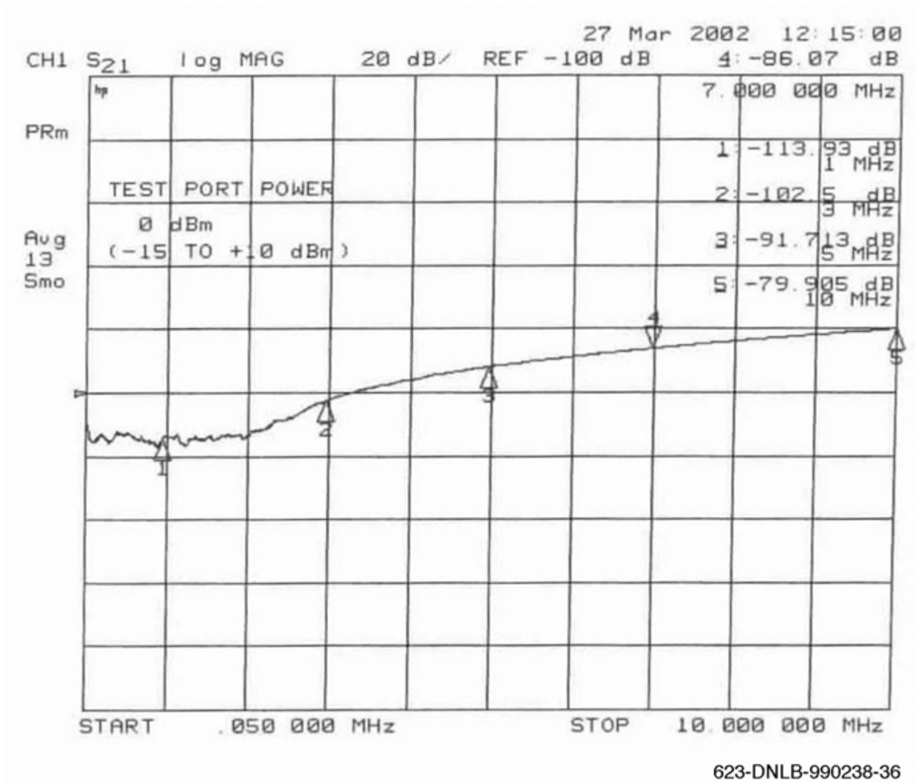

Figure 100. Transmission coefficient (t) of tinsel wire air core transformer across the 50 KHz to 10 MHz frequency range

3.4.2.2 Trial 2

In light of the results achieved with the above structure we decided to conduct experiments using a lower impedance wire. This experiment allowed us to develop the basic approach for designing the system for efficient power transfer. The transformer coils used in this trial were made from 16 turns of a No. 24 enameled magnet wire. To achieve better transfer efficiency we continued to use a 50Ω resistor across the secondary coil. The measured impedance values of these loops are shown in Tables 19 and 20.

Figure 101 shows the reflection coefficient of Coil I over the 50 KHz to 10 MHz frequency range. The graph shows that this transformer coils has a self-resonance at 236 KHz as evidenced by the drastic drop in reflected energy at that frequency. The reflected energy coefficient was

Table 19. Effects of frequency on loop impedance for magnet wire coil No. 1

16 Turn Magnet Wire. Coil I	Resistance (Ω)	Reactance (Ω)	Impedance (Ω)
1 MHz	4.98	196.9	4.98 + (196.9)i
3 MHz	160.4	787.4	160.4 + (787.4)i
5 MHz	2129.8	554.1	554.1 + (554.1)i
7 MHz	762.8	-905.0	762.8 – (905)i
10 MHz	250.3	-5201.7	250.3 – (5201.7)i

Table 20. Effects of frequency on loop impedance for magnet wire coil No. 2

16 Turn Magnet Wire. Coil II	Resistance (Ω)	Reactance (Ω)	Impedance (Ω)
1 MHz	3.95	155	3.95 + (155)i
3 MHz	97.4	616.5	97.4 + (616.5)i
5 MHz	2030.0	927.6	2030.0 + (927.6)i
7 MHz	656.4	-869.6	656.4 – (869.6)i
10 MHz	183.6	-4641.8	183.6 – (4641.8)i

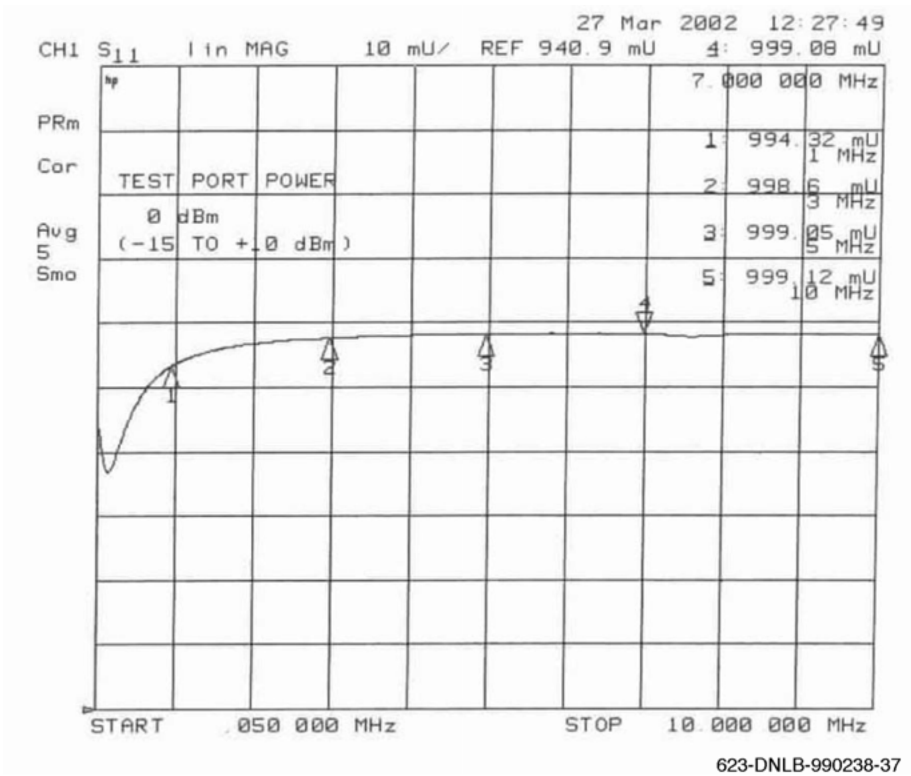

Figure 101. Reflection coefficient of magnet wire coil over the 50 KHz to 10 MHz frequency range

found to behave similarly for Coil II as well. This information indicates that optimum transfer efficiency will be achieved by operating near 236 KHz. To gain a better understanding of this frequency range further impedance measurements were taken for Coil I as shown in Table 21.

Once the individual coils had been characterized they were taped together to form the air core transformer. The transfer coefficient and reflection coefficient were then measured as shown in Figures 102 and 103, respectively. These plots indicated that the maximum transmission occurred in the vicinity of 442 KHz, relatively close to the 236 KHz region that was anticipated. The optimum transfer efficiency in this region was determined to be 41 percent.

Table 21. Effects of frequency on loop impedance for magnet wire coil No. 2

16 Turn Magnet Wire. Coil I	Resistance (Ω)	Reactance (Ω)	Impedance (Ω)
51 KHz	0.37	10.2	0.37 + (10.2)i
90 KHz	0.42	14.0	0.42 + (14.0)i
153 KHz	0.78	30.5	0.78 + (30.5)i
203 KHz	0.97	40.4	0.97 + (40.4)i
1 MHz	3.95	155.0	3.95 + (155.0)i

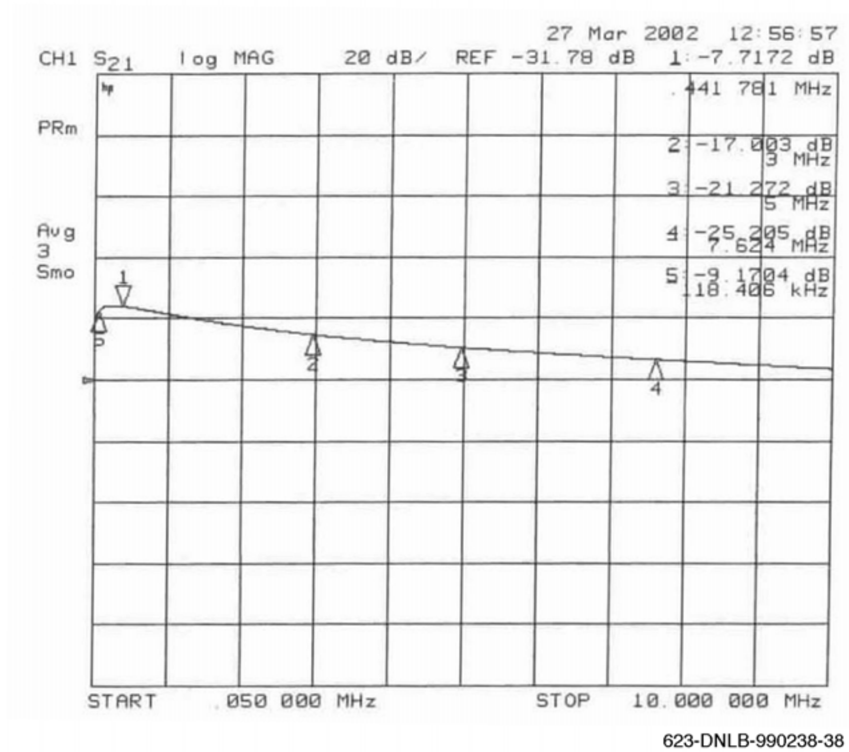

Figure 102. Transfer coefficient for magnet wire air core transformer

This trial indicates that respectable increases in transfer efficiencies can be achieved if the transformer coils have sufficiently low impedance. It can also be seen that for optimum transfer efficiency we are restricted to operation in a relatively narrow bandwidth. This fact, while inconsequential for power transfer, severely limits the use of transformer coupling for data transmission. Efficient data transfer requires good broadband efficiency.

3.4.2.3 Trial 3

Trial 2 showed that a marked increase in transfer efficiency was attained when a lower impedance loop was used. We decided to evaluate power transfer efficiency in this next trial using a more textile compatible conductor. A 22 AWG silver coated copper wire comprising 66 strands of 40 AWG filaments was selected due to its low stiffness and successful

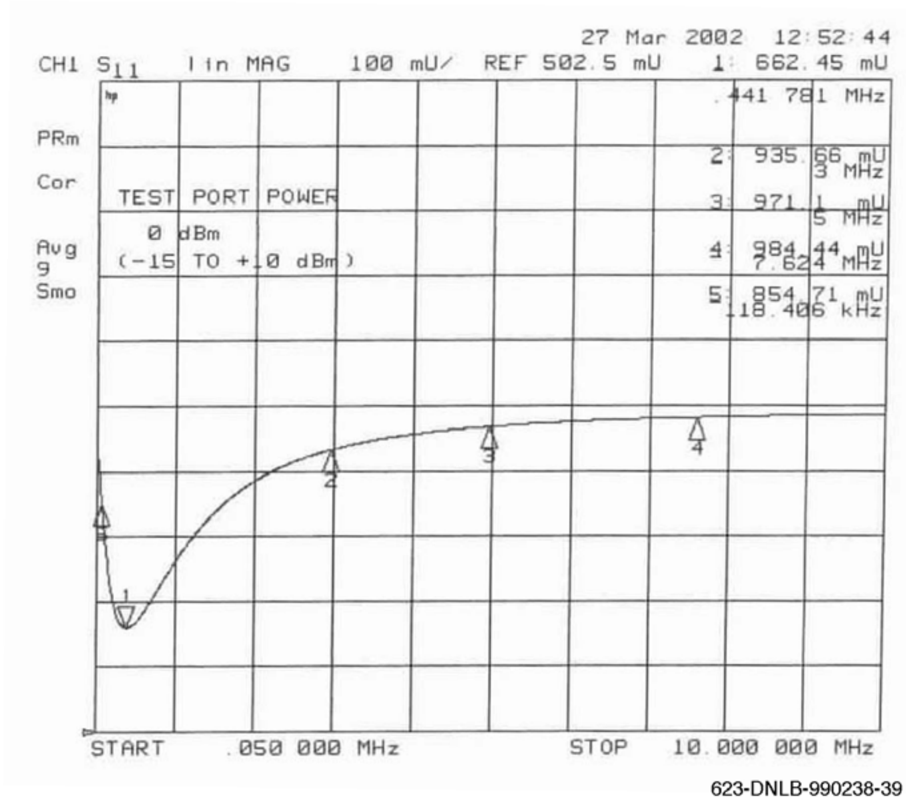

Figure 103. Reflection coefficient for magnet wire air core transformer

implementation as the power conductors in the USB v2 cable. The inductance of this wire is approximately 0.1 to 0.2 Ω/meter. The wire insulation was a PET-based soft flexible coating. Based on the results from the previous trial we concentrated our efforts on the 50 KHz to 1 MHz frequency range where better transfer efficiencies can be achieved. Tables 22 and 23 show the impedances measured for the two copper wire coils.

Given the good impedance of these coils we decided to further improve the transfer efficiency by using a series-parallel capacitance circuit to tune the system. This circuit helped to improve efficiency by canceling reactances and transforming the impedance of the system. The resulting transfer coefficient and reflection coefficient plots are shown in Figures 104 and 105, respectively. These plots show that optimum transfer occurs at 760 KHz. Comparing these plots to Figures 104 and 105, we see that transmission efficiency has improved but the bandwidth has decreased. The transfer efficiency calculated using the transfer coefficient is 91 percent while

Table 22. Effects of frequency on loop impedance for 22 AWG Silver coated copper wire coil No. 1

10 Turn, 22 AWG AG/CU. Coil I	Resistance (Ω)	Reactance (Ω)	Impedance (Ω)
50 KHz	0.12	3.3	0.12 + (3.3)i
100 KHz	0.12	6.6	0.12 + (6.6)i
300 KHz	0.21	19.8	0.21 + (19.8)i
600 kHz	0.36	39.5	0.36 + (39.5)i
1 MHz	0.6	565.9	0.6 + (565.9)I

Table 23. Effects of frequency on loop impedance for 22 AWG silver coated copper wire coil No. 2

10 Turn, 22 AWG AG/CU. Coil II	Resistance (Ω)	Reactance (Ω)	Impedance (Ω)
50 KHz	0.14	3.3	0.14 + (3.3)i
100 KHz	0.15	6.6	0.15 + (6.6)i
300 KHz	0.26	19.7	0.26 + (19.7)i
600 kHz	0.43	39.4	0.43 + (39.4)i
1 MHz	0.7	565.7	0.7 + (565.7)i

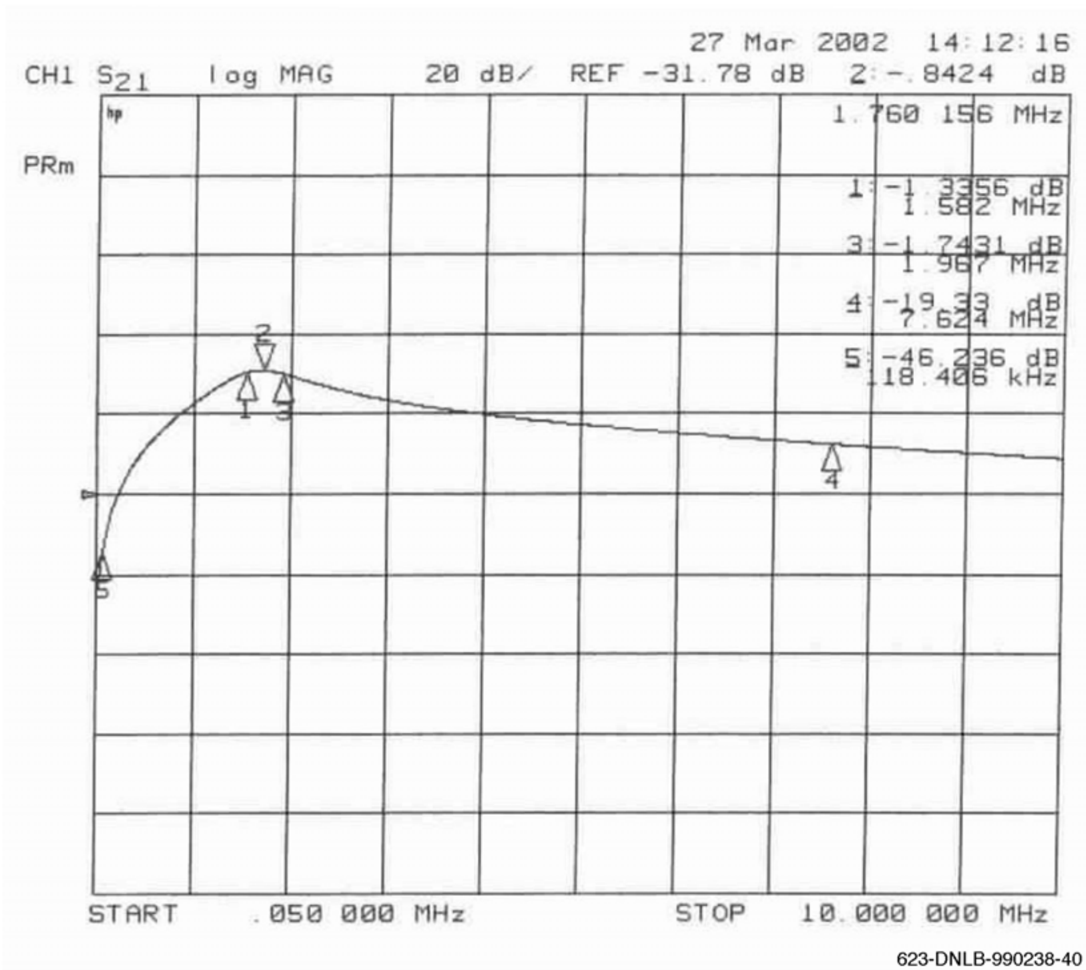

Figure 104. Transfer coefficient for 22 AWG silver coated copper wire air core transformer

that calculated using the reflection coefficient is 94 percent. This 3 percent discrepancy is due to losses in the matching circuit and the coils themselves. As stated before, narrow bandwidth is not an issue for power transfer. The DC-to-DC transformer that will be used in the envisioned system will operate at one RF frequency. The only way the narrow bandwidth may effect the system is when it is turned it on and off (oscillate or switch on and off). Switching may result in slight loss in efficiency. In similar DC-to-DC power transformers, efficiencies of 95 percent are routinely achieved.

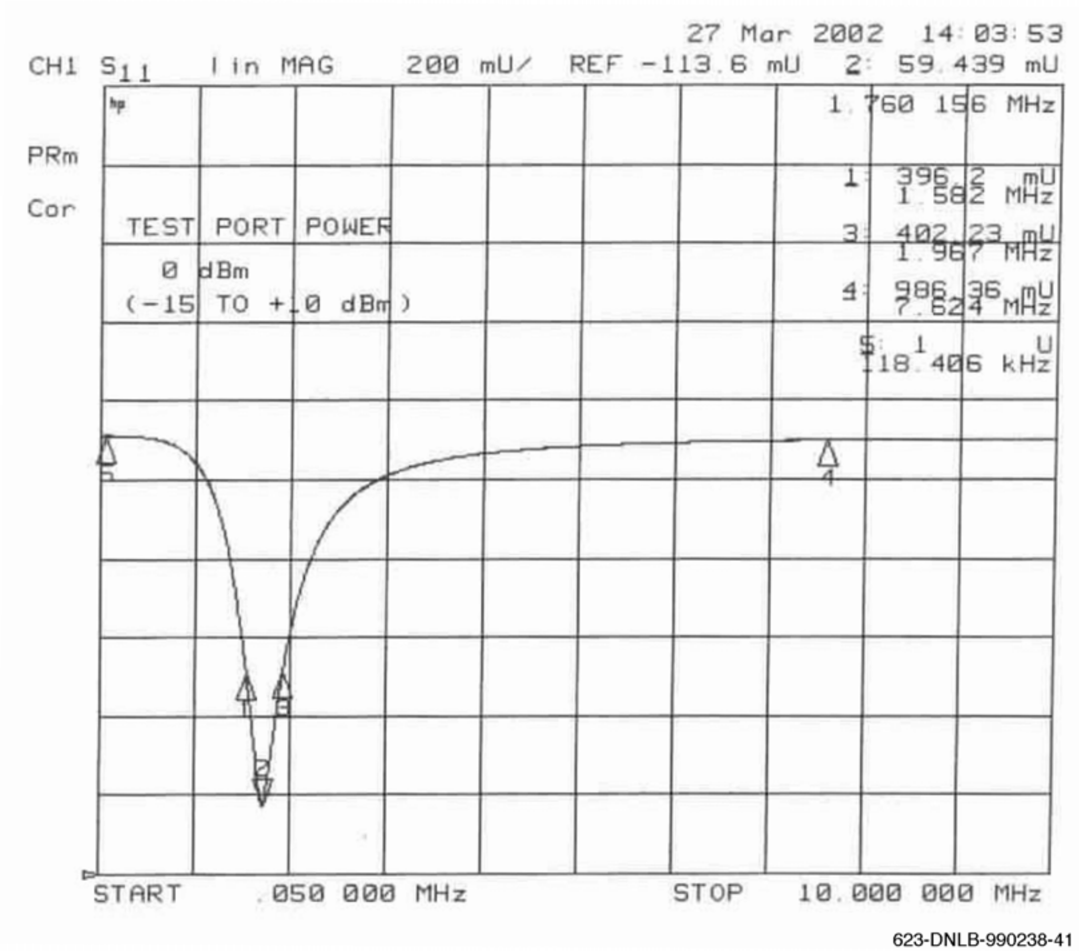

Figure 105. Reflection coefficient for 22 AWG silver coated copper wire air core transformer

3.4.2.4 Geometry Effects

As anticipated, experimentation showed that transfer losses between the coils were directly proportional to the degree of misalignment of the two coils. In order to provide maximum transfer efficiency, the two coils need to be kept in alignment even when the soldier is in motion. This issue was successfully addressed by adding Velcro pads on the sides of transformer coils as shown in Figure 106. Locating the coils in areas that experience the least misalignment, such as the shoulder area, should also help reduce transfer efficiency losses.

3.5 Task 5 - Network Integration and Testing; Task 6 - Refine Network Design and Task 7 - Build Test and Deliver Prototype Network

Discussions with Andy Taylor of Natick and Jack Tyrell of Exponent identified a potential soldier system application which could be easily networked using the Phase II cables for demonstration purposes. Exponent is currently manufacturing and delivering a set of new MILES prototypes for training purposes. The new system incorporates an improved sensor network. As the cables on the system either use a USB protocol or a protocol that is inherently

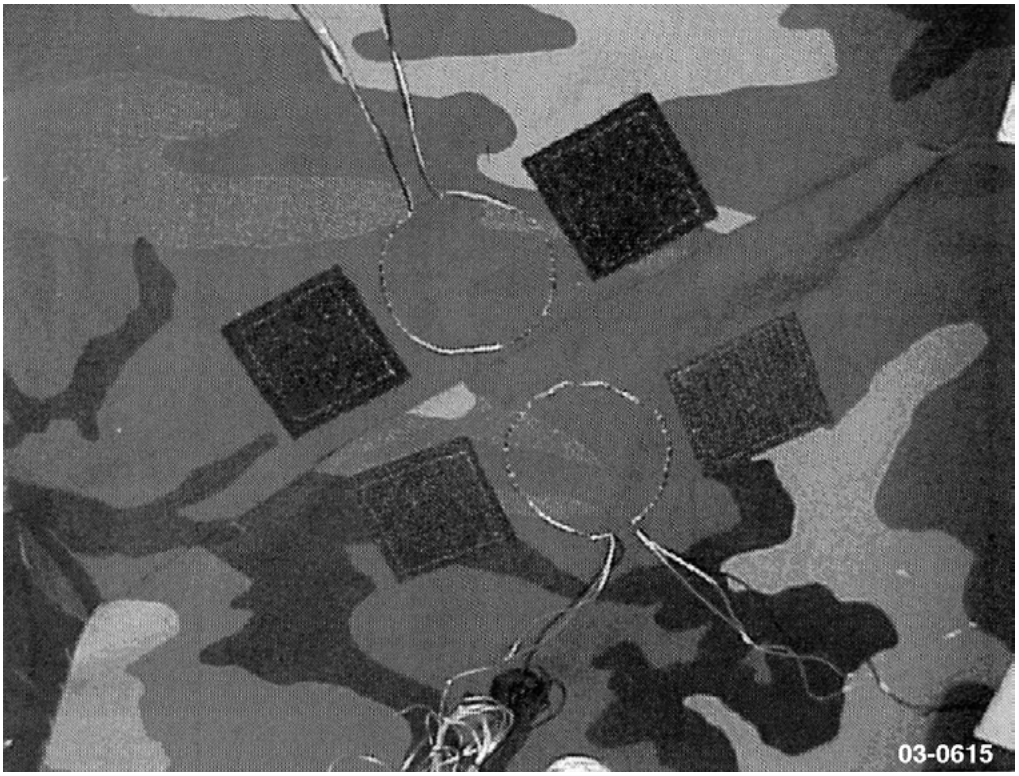

Figure 106. Velcro pads are used to maintain relative proximity of coils for maximum efficiency

similar in cable design to the USB cable, they suggested that we could provide cables for integration. We were given a contact at Rapitec (Upland, CA), the manufacturer of the MILES system, to coordinate the manufacture and delivery of the new cables for integration into the prototypes MILES systems.

We decided that providing the cables to this application would be an excellent demonstration vehicle since the prototypes could potentially be put through a larger set of tests by the Army than originally planned for the cables to be delivered on this program. Confirmation of this plan was made with the Contracting Officer's Technical Representative. Three cables used on the MILES system were identified as candidates. They are listed in Table 24. As can be seen in the

Table 24. Cables for integration into MILES

Cable	Construction	Connectors (End – End)
External USB interface to Body worn computer for data download after exercise	USB 2.0 construction	USB A and 5-Pin Lemo
Computer to Hornbox (all body worn)	5 conductor – 3 single conductors and one shielded twisted pair	5-pin Lemo and 5-Pin Lemo
Computer to Breakaway connector to Halo Sensor	5 conductor – 3 single conductors and one shielded twisted pair	Hardwired and 5-pin Lemo

table, the cables either use the technology already developed under this program or a slight modification of the technology by the addition of an additional single conductor.

After further consultations with Exponent we decided that the computer interface cable used for data download was the best choice for demonstrating the technology developed during this program. This cable was a logical choice as one end used a USB A connector for which we had already developed a mold. The plan was to first connectorize lengths of cable with USB A connectors on both ends. These cables would then be cut in half, connectorized with 5-conductor 0F Lemo connectors and then overmolded. Jack Tyrell of Exponent suggested that Thor Electronics be used to overmold the Lemo connectors as they had experience in this area.

Foster-Miller modified a run of the USB v2 cable at Offray to produce approximately 35 yards of cable for the computer interface. The width of this modified cable was narrowed from 1 in. to 3/4 in. since it did not need to be sewn down, and a third 22 AWG power conductor was added, bringing the total conductor count to 5. Eight-foot lengths of the 5-conductor cable were then shipped to Plastics One to be connectorized on both ends with USB A connectors. Plastics One found that the floating pins that were used to hold the wider USB v1 and v2 in place were spaced to far apart to work properly, which resulted in textile show-through and misalignment of the cable as shown in Figure 107. As a result a second batch of cables had to be connectorized using USB v2.

Samples of our cables were sent to Thor Electronics to assess their compatibility with their overmolding process. The results of these preliminary overmolding trials (Figure 108) indicated

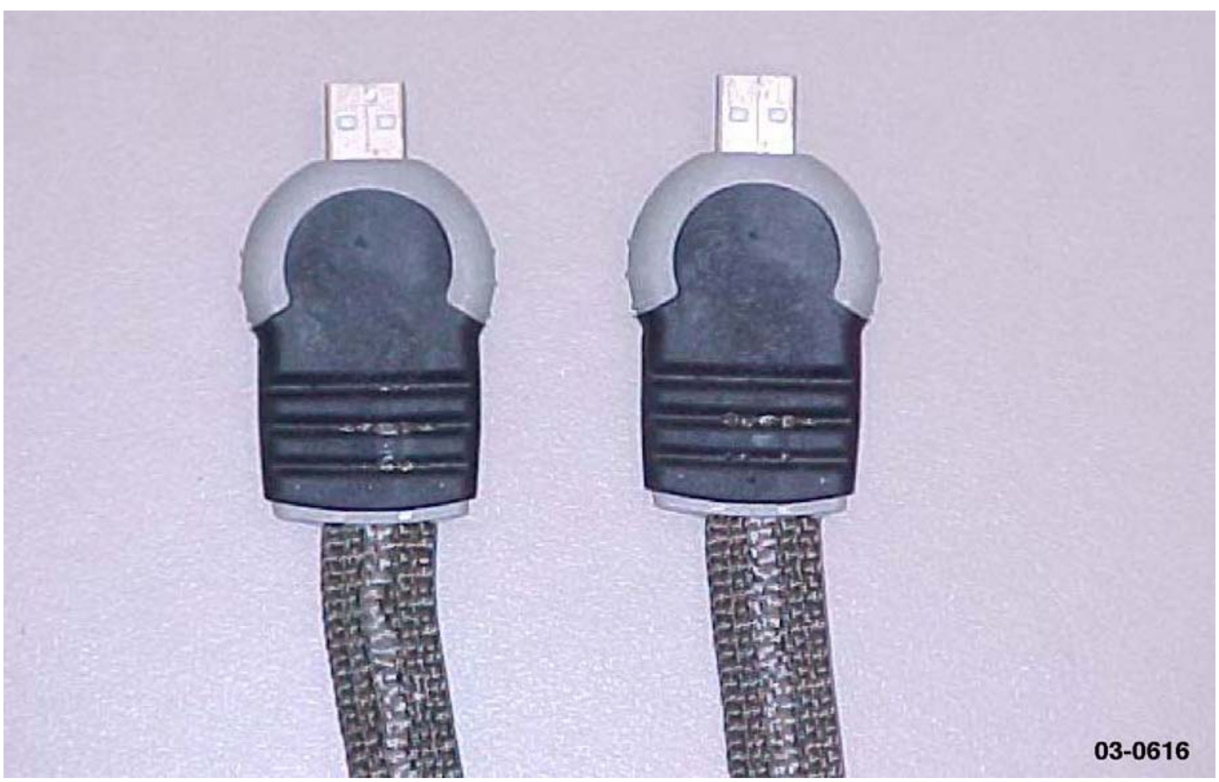

Figure 107. 5-conductor cable terminated with USB connector

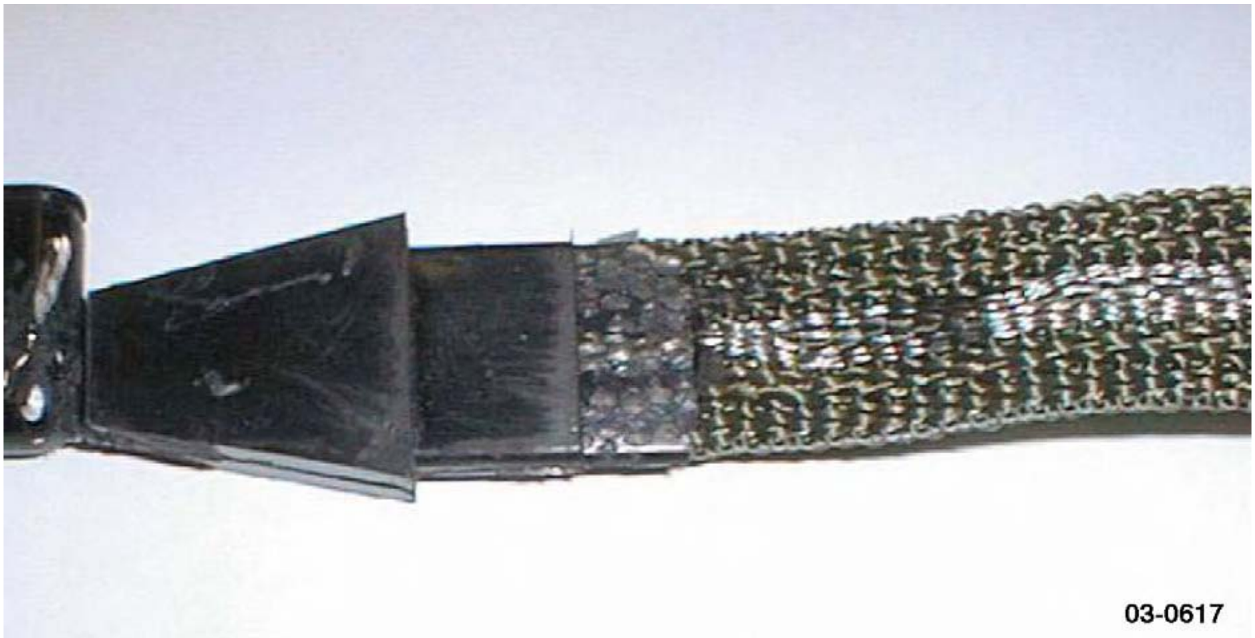

Figure 108. Polyurethane overmolding trial at Thor Electronics

that there were some issues that needed to be addressed with regards to flashing of the overmolding material. Thor's process uses a room temperature, low viscosity polyurethane. Due to the low heat and pressure requirements of this process, mold tooling and part costs are lower than with the hot melt injection process favored by Plastics One.

The polyurethane also provides a strong bond between the connector and the textile even though they are composed of dissimilar materials, due to the low viscosity of the polyurethane which allows it to soak into the cable's nylon yarns (Figure 109). The molten nylon used in the hot melt injection process has a significantly higher viscosity that only allows it to flow within the spaces between the nylon yarns (Figure 109).

The differences in bonding as a function of viscosity are due to the fact that the USB textile has two characteristic length scales, L_1 and L_2, which are dramatically different. This length scales lead to dramatically different values of permeability. The relationship between the viscosity of a fluid and its ability to flow through a porous material is described in part by Darcy's Law:

$$q = -\left(\frac{k}{\mu}\right)\frac{dP}{dx}$$

Here k is the permeability of the porous material, μ is the viscosity of the fluid, q is the rate of fluid flow through the porous media and dp/dx is the fluid pressure gradient. Stated more simply, this relationship indicates that using a higher viscosity overmolding material to impregnate a given textile will require a higher mold pressure. This solution is obviously an expensive one that should be avoided if possible.

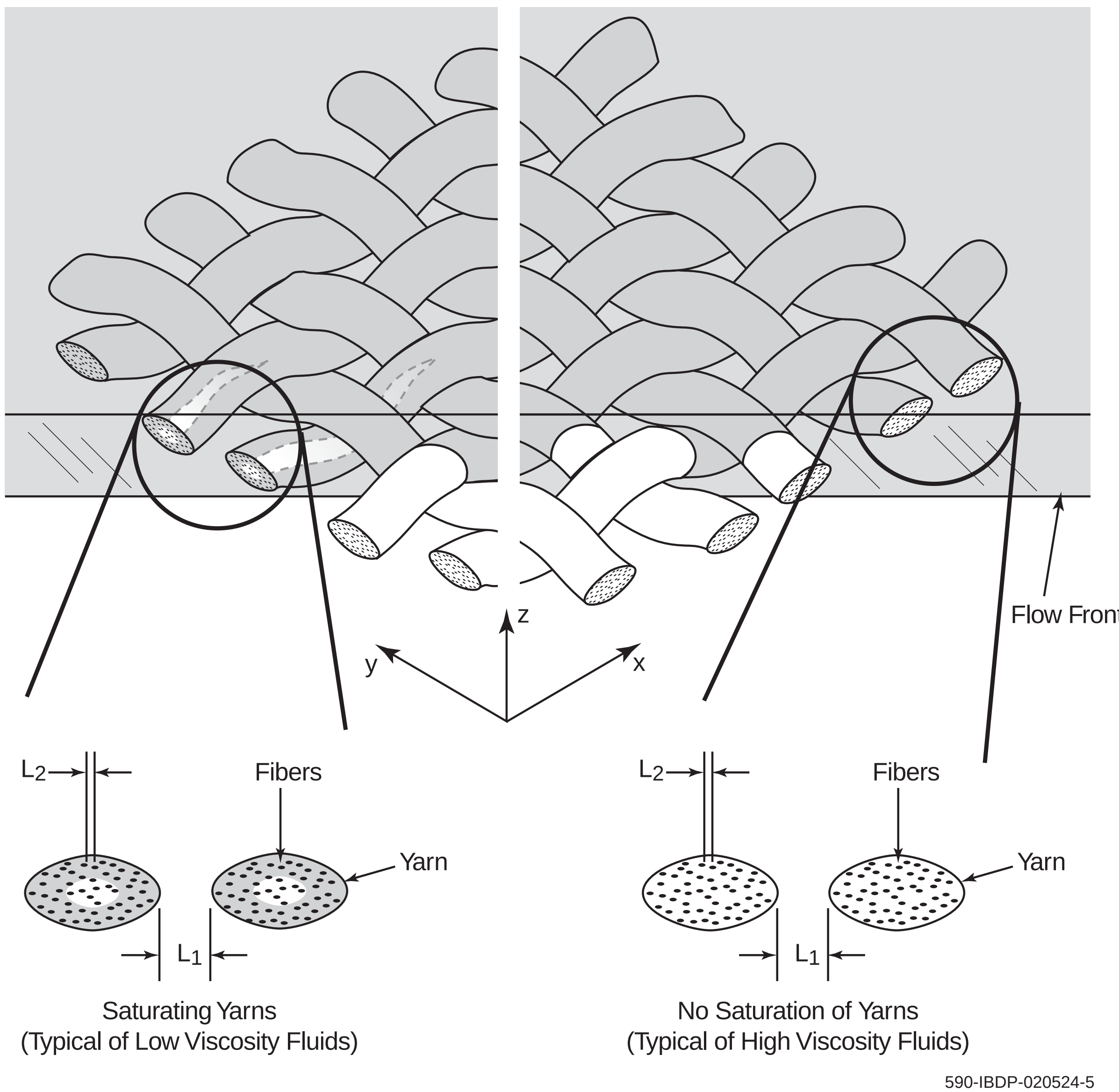

Figure 109. Effect of polymer viscosity and textile permeability on bonding

Whereas the polyurethane overmold relies on its low viscosity to form a mechanical bond with the textile structure, the molten nylon used in the hot melt injection process uses its high temperature and molecular compatibility with the nylon fabric to create a fusion bond. This bond occurs when the molten nylon melts the surface filaments of the nylon yarns sufficiently to allow intermingling of the polymer chains. Intermingling creates a powerful bond without the need for saturation of the yarns. This approach is limited however to the use of the same material for the substrate textile and overmolding since dissimilar polymer chains resist intermingling.

Once the parties involved were comfortable with the choice of electrotextile cable, connector and overmolding technique Thor Electronics was asked to provide tooling for an overmold (Figure 110 and 111). This tooling was quickly rejected however as it was unnecessarily wide and angular. A second tooling set was then fabricated with a smaller and more rounded form

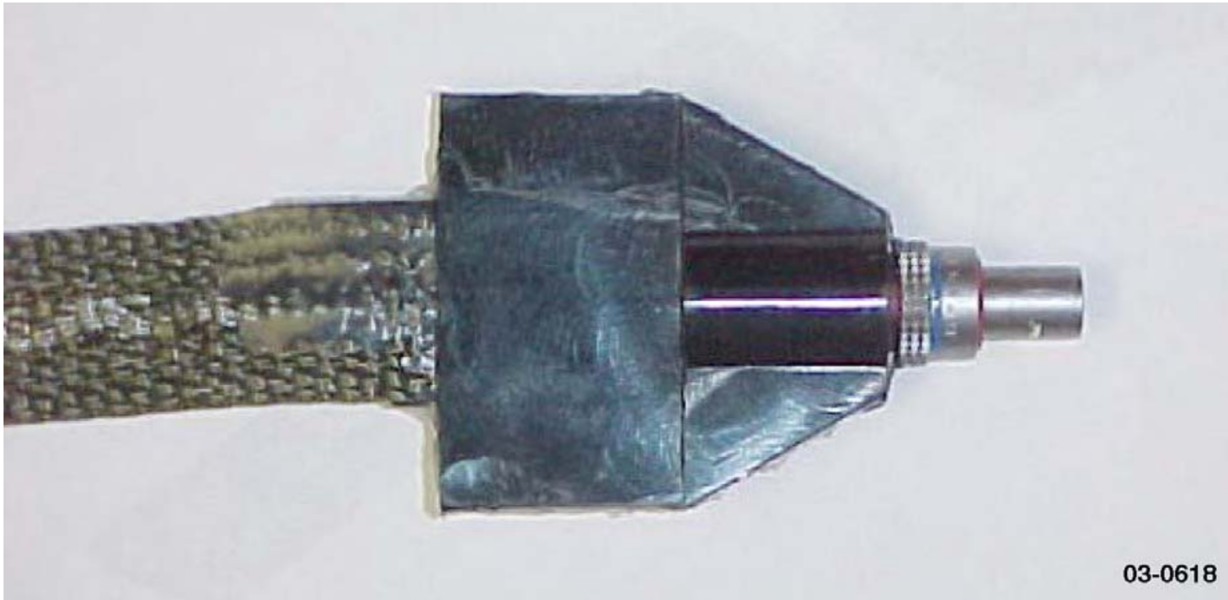

Figure 110. Prototype 5-pin lemo thermoset overmold (top view)

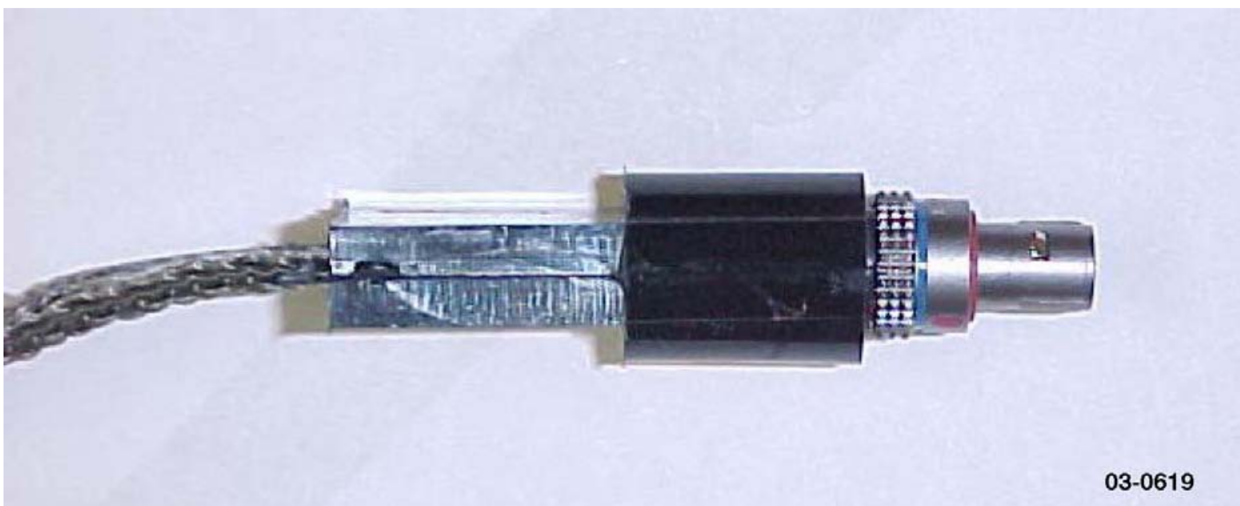

Figure 111. Prototype 5-pin lemo thermoset overmold (side view)

factor (Figure 112). Due to time and financial constraints this mold was made using a Selective Laser Sintering (SLS) technique, rather than cut steel. Despite the continued presence of flash as shown in Figures 113 and 114 this modified overmold was considered suitable for system integration. Once lengths of the USB v2 cable were appropriately connectorized with a USB connector on one end and a Lemo connector on the other (Figure 115) they were shipped back to Foster-Miller for integration into a MOLLE vest. Figures 116a and 116b show one of the many possible implementations of this electrotextile cable assembly.

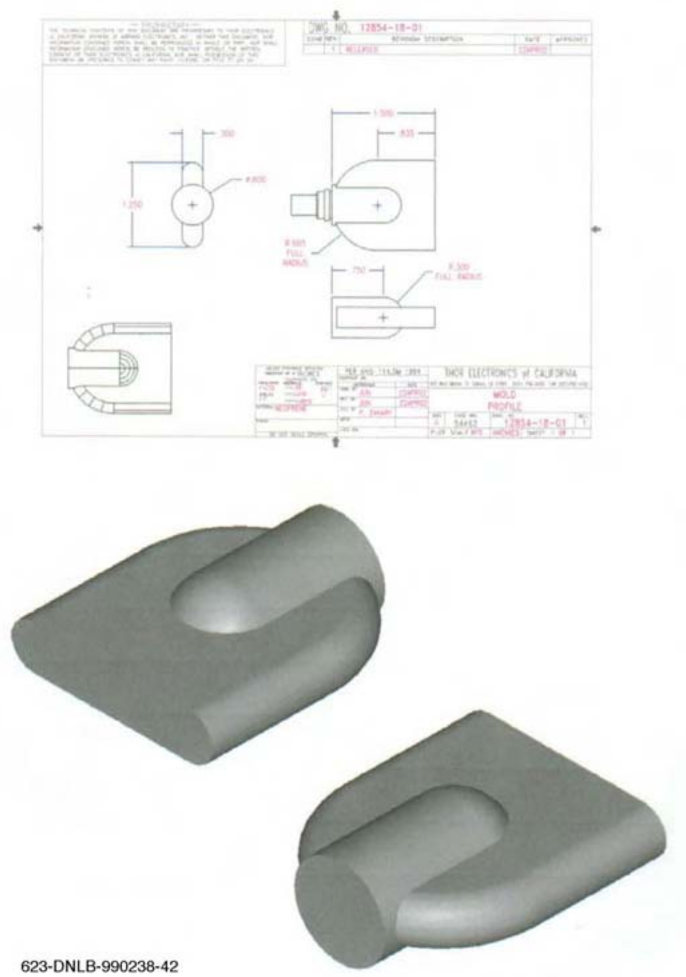

Figure 112. Refined concept for prototype 5-pin lemo overmold

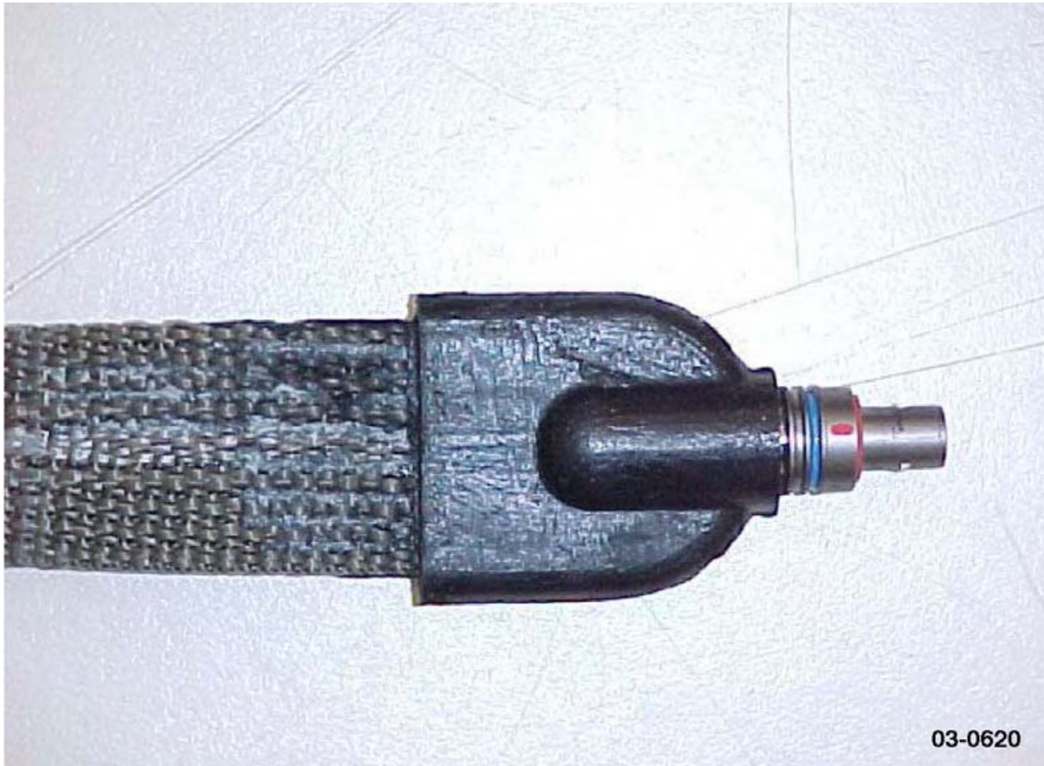

Figure 113.   5-pin lemo overmold (top view) with USB v2 cable

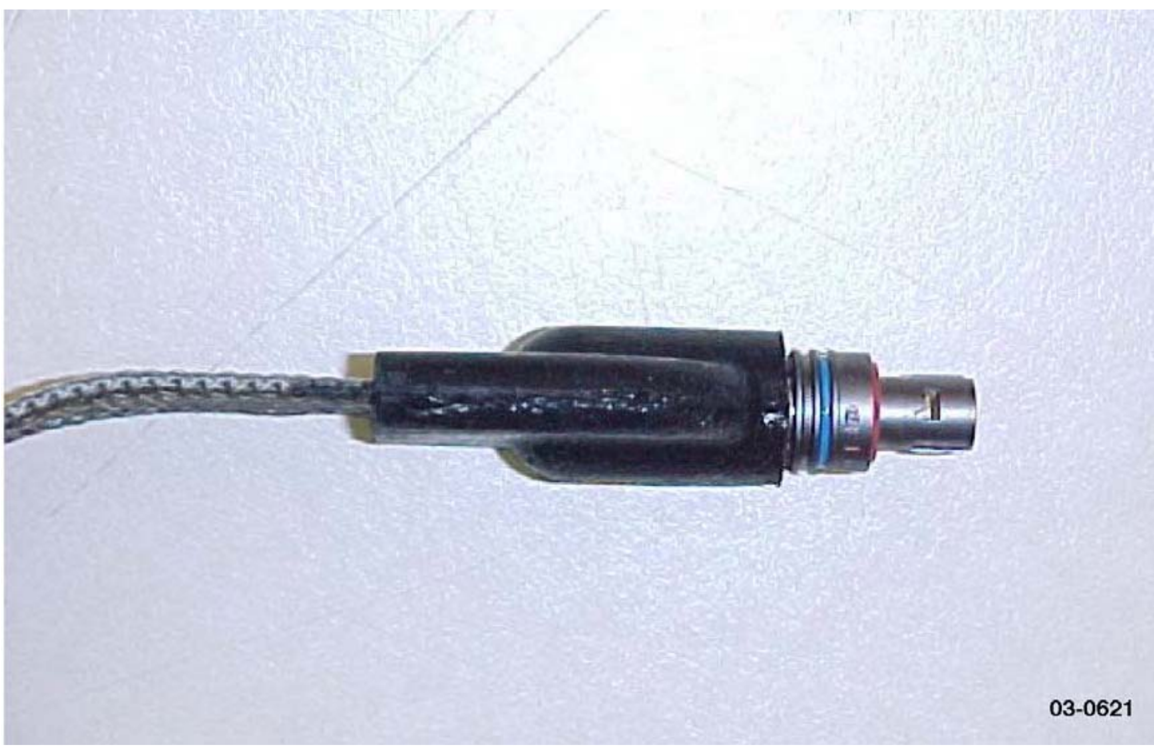

Figure 114.   5-Pin lemo overmold (side view) with USB v2 cable

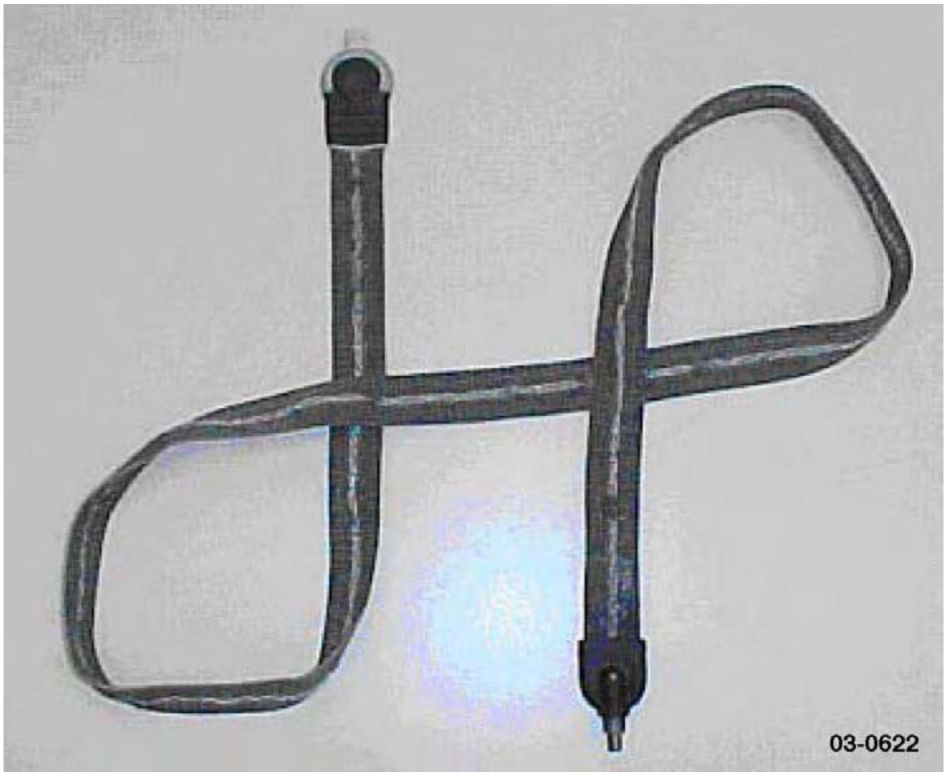

Figure 115. USB Type A to 5-pin lemo cable

a) b)

Figure 116. 5-pin lemo to USB cable assembly integrated into standard MOLLE vest with pouches for electronics modules, radio, batteries, etc. a) front view b) back view

4. RESULTS AND CONCLUSIONS

4.1 Cable Design and Material Selection

USB 2.0 is the preferable standard for soldier borne personal area networks as it permits high data rate, ad-hoc reconfigurability with hot swapping capabilities.

In the near term, copper-based electrotextile data cables are preferable to electro-optic cables. This advantage is due to the commercial, logistical and safety concerns associated with implementing an optical network.

Replacing the Aluminum/Mylar shielding used in standard USB cable designs with a braided shielding made from electrotextiles provides several advantages, including better shielding effectiveness, increased flexibility and extended flex life.

Testing revealed that nylon webbing can withstand considerable loading, fatigue and wear-related abuse if a sufficiently tight structure is used. Woven cables are therefore preferable to braids.

Stiffness testing results showed that standard electro-optic components contribute a significant portion to the overall cable stiffness. Several methods of decreasing the stiffness of these components were identified:

- Use of softer, lower durometer, insulations on all wires.
- Use of highly stranded conductors.
- Replacement of the standard foil shielding with a hollow braid of metal clad fibers.

4.2 Safety Issues

Short chopped stainless steel and/or nylon fibers generated during trimming may come in contact with the skin or become airborne and get into the respiratory system depending on the local airflow. This situation has been found to cause limited irritation in some individuals. To reduce these effects, it is recommended that the denier of the individual nylon filaments be changed if MIL-SPEC allows to reduce the potential for skin irritation from short coarse fibers. In addition, the remedial coating procedure taken by Malden Mills to protect the stainless steel yarn should be used in future weavings to limit fiber breakage. It is also recommended that when trimming or post-trimming to length the narrow wovens, all persons wear the following safety equipment:

- Gloves.
- Safety glasses.
- Lab coats.

During any trimming operations, either a dust mask or a suction airflow should be used at the station to avoid breathing the fibers into the respiratory system.

4.3 Connector Overmold

Connector interfaces should be rectilinear. Most commercial connectors are round in profile and scale fast in dimension when the number of pins increases. An overall flat and rounded edge profile is most appropriate for body-born connectors that are on the torso.

The plug-in motion of a lap-top PC type connector is not ideal for body-borne use. The plugging motion requires that the cable leave the plane of the clothing, requiring extra material for the plugging action. A snapping or sliding motion should be investigated.

While the premold/overmold concept worked well in this program, it is labor intensive. Future work should investigate monolithic mold designs.

When selecting an overmolding material, care should be taken that its injection temperature does not exceed that of the wiring insulation or shorting may occur. If a low-temperature overmolding material is not available, the molding material should not come into contact with any exposed wires. Prepotting or premolding the wires with a lower temp barrier material is an effective technique for protecting the insulation.

An adequate number of positioning pins should be included at the outset of mold design to prevent cable washout and textile showthrough.

This document reports research undertaken at the U.S. Army Natick Soldier Research, Development and Engineering Center, Natick, MA, and has been assigned No. NATICK/ TR-11/004 in a series of reports.

5. REFERENCES

1. Devine, M., “Physical Fightability Evaluation Methodology,” The Natick OFW Open Reviews, October 2-4, 2001.
2. Gemperle, F., Kasabach, C., Stivoric, J., Bauer, M., and Martin, R., “Design for Wearability,” The Second International Symposium on Wearable Computers, October 19-20, 1998.
3. Embedded Antenna Loops for the VHF-UHF, Phase I, DAAB07-01-C-L710, COTR: Ms Cynthia Baroni
4. Electro-optic Fabrics for the Warrior of the 21st Century, Phase I, DAAN02-98-P-8523, COTR: Ms. Carole Winterhalter, (508) 233-5460.

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APPENDIX A

SHIELDING EFFECTIVENESS AND GROUP 6 SIGNAL INTEGRITY TEST RESULTS

November 3, 2000

TEST REPORT #200016

USB 2.0 Qualification
Group 6

Foster Miller

APPROVED BY: George G. Olear II
DIRECTOR OF MECHANICAL/ENVIRONMENTAL TESTING
CONTECH RESEARCH, INC.

CERTIFICATION

This is to certify that the evaluation described herein was designed and executed by personnel of Contech Research, Inc. It was performed in concurrence of Foster Miller, who was the test sponsor.

All equipment and measuring instruments used during testing were calibrated and traceable to NIST according to ISO 10012-1 and ANSI/NCSL Z540-1, as applicable.

All data, raw and summarized, analysis and conclusions presented herein are the property of the test sponsor. No copy of this report, except in full, shall be forwarded to any agency, customer, etc., without the written approval of the test sponsor and Contech Research.

George G. Olear II
Director of Mechanical/Environmental Testing
Contech Research, Inc.

GGO:

REVISION HISTORY

DATE	REV. NO.	DESCRIPTION	ENG.
11-3-00	Rev. 1.0	Initial Issue.	ggo

SCOPE

1. To perform compliance testing on USB cables as submitted by the test sponsor, Foster Miller.

APPLICABLE DOCUMENTS

1. Unless otherwise specified, the following documents of issue in effect at the time of testing performed form a part of this report to the extent as specified herein. The requirements of sub-tier specifications and/or standards apply only when specifically referenced in this report.

2. Standards:

   EIA Publication 364
   USB 2.0

TEST SAMPLES AND PREPARATION

1. The following test samples were submitted by the test sponsor, Foster Miller, for the evaluation to be performed by Contech Research, Inc..

   USB Proprietary cable

2. The test samples as submitted were certified by the manufacturer as being fabricated and assembled utilizing normal production techniques common for this type of product and inspected in accordance with the quality criteria as established for the product involved.

3. All test samples were coded and identified by Contech Research to maintain continuity throughout the test sequences. Upon initiating testing, mated test samples remained with each other throughout the test sequences for which they were designated.

TEST SELECTION

1. All tests were performed in accordance with the applicable sequences and procedures as specified in USB 2.0.

2. The following test group was established:

Examination
|
Impedance
|
Attenuation
|
Propagation Delay
|
Propagation Delay Skew
|
Capacitive Load /1
|
Shielding Effectiveness /2

/1 Not Required for High Speed
/2 Performed by NTS

SAMPLE CODING

1. All samples were coded. Mated test samples remained with each other throughout the test group/sequences for which they were designated. Coding was performed in a manner which remained legible for the test duration.

2. The test samples were coded in the following manner:

Test Group	Cable #	Code
Group 6	1	6-1
	2	6-2
	3	6-3

DATA SUMMARY

TEST	REQUIREMENTS	RESULTS
Group 1		
Examination	No damage	N/A
Mating Forces	35 N max	N/A
LLCR	30 milliohm max initial	N/A
Durability	No Damage	N/A
Vibration	No Chatter > 1 microsecond	N/A
Mechanical Shock	No Chatter > 1 microsecond	N/A
LLCR	10 milliohm max change	N/A
Unmating Forces	10 N minimum	N/A
Cable Pullout	No Damage or loss of cont.	N/A
Group 2		
Examination	No Damage	N/A
LLCR		N/A
Durability		N/A
Temperature Life		N/A
LLCR		N/A
Group 3		
Examination	No Damage	N/A
LLCR		N/A
Durability		N/A
MFG		N/A
LLCR		N/A
Group 4		
Examination	No damage	N/A
Capacitance		N/A
IR		N/A
DWV		N/A
Thermal Shock		N/A
Humidity		N/A
IR		N/A
DWV		N/A
Group 5		
Examination	No Damage	N/A
Solderability	95% Coverage	N/A

DATA SUMMARY CONT.

Group 6		
Examination	No Damage	PASS
Impedance	76.5 to 103.5	PASS
Attenuation	3.2 dB and 5.8 db max between 200 and 400 Mhz	PASS
Propagation Delay	5.2 nS/m max.	PASS
Propagation Delay Skew	100 pS max.	PASS
Capacitive Load	200 to 450 pF	PASS
Shielding Effectiveness	20 dB between 30 Mhz and 1 Ghz	PASS
Group 7		
Examination	No Damage	N/A
Critical Dimension		N/A
Group 8		
Examination	No Damage	N/A
Cable flex	Continuity loss 1 microsec Physical damage	N/A
DWV	No leakage or breakdown	N/A
IR	1000 Mohm min	N/A

TEST RESULTS

Group 6

PROJECT NO.: 200016	SPECIFICATION: USB 2.0
PART NO.: none	PART DESCRIPTION: cable
SAMPLE SIZE: 3	TECHNICIAN: MOB
START DATE: 9-18-00	COMPLETE DATE: 9-18-00
ROOM AMBIENT: 21 °C	RELATIVE HUMIDITY: 64 %
EQUIPMENT ID#: none	

VISUAL, INITIAL

PURPOSE:

1. To assure that test samples to be tested meet the workmanship standards normal for the product being tested and have not sustained any damage during shipment.

2. To assure that the marking conforms to the products received and to be tested.

PROCEDURE:

1. The test samples were visually inspected under 10X magnification for any damage, distortion, marking conformance and legibility, etc.

REQUIREMENTS:

1. The test samples shall show no evidence of physical damage, distortion, chipping, etc., which will adversely affect serviceability or appearance.

2. The marking shall be legible and intact.

3. The contacts shall exhibit no cracks or peeled plating.

RESULTS:

1. All cables so examined met the requirements as specified.

PROJECT NO.: 200016	SPECIFICATION: USB 2.0
PART NO.: none	PART DESCRIPTION: cable
SAMPLE SIZE: 3	TECHNICIAN: MOB
START DATE: 9-19-00	COMPLETE DATE: 9-28-00
ROOM AMBIENT: 22 °C	RELATIVE HUMIDITY: 52 %
EQUIPMENT ID#: 475,1147,1148	

CHARACTERISTIC IMPEDANCE VIA TIME DOMAIN (TDR)

PURPOSE:

1. To determine the Characteristic Impedance of the transmission system under test.

PROCEDURE:

1. The test was performed in accordance with EIA 364, Test Procedure 108.

2. Test Conditions:

   Rise Time : 200 ps

REQUIREMENTS:

The characteristic impedance shall be 76.5 to 103.5 ohms.

RESULTS:

The following is a summary of the data observed in milliohms:

5 Meter

"A" Connector				"B" Connector			
Sample ID	MIN	MAX	AVG	Sample ID	MIN	MAX	AVG
6-1	90.3	100.2	95.3	6-1	88.1	101.0	94.6
6-2	89.1	101.6	95.4	6-2	90.3	101.5	95.9
6-3	89.9	102.1	96.0	6-3	90.5	102.7	96.6

4 Meter

"A" Connector				"B" Connector			
Sample ID	MIN	MAX	AVG	Sample ID	MIN	MAX	AVG
6-1	88.0	99.1	93.6	6-1	88.9	99.3	94.1
6-2	88.3	99.2	93.8	6-2	88.6	99.3	93.9
6-3	89.6	99.4	94.5	6-3	88.8	100.0	94.4

3 Meter

"A" Connector				"B" Connector			
Sample ID	MIN	MAX	AVG	Sample ID	MIN	MAX	AVG
6-1	88.9	97.5	93.2	6-1	88.6	98.0	93.3
6-2	87.7	96.9	92.3	6-2	87.1	97.7	92.3
6-3	88.6	97.7	93.2	6-3	89.1	97.6	93.4

2.5 Meter

"A" Connector				"B" Connector			
Sample ID	MIN	MAX	AVG	Sample ID	MIN	MAX	AVG
6-1	88.8	97.7	93.3	6-1	89.3	99.8	94.6
6-2	88.4	96.8	92.3	6-2	88.3	96.6	92.5
6-3	88.5	95.9	92.2	6-3	88.0	98.1	93.1

2 Meter

"A" Connector				"B" Connector			
Sample ID	MIN	MAX	AVG	Sample ID	MIN	MAX	AVG
6-1	89.0	98.9	94.0	6-1	88.7	96.1	92.4
6-2	88.5	95.8	92.2	6-2	88.7	96.0	92.4
6-3	89.4	101.2	95.3	6-3	88.6	98.3	93.5

1 Meter

"A" Connector				"B" Connector			
Sample ID	MIN	MAX	AVG	Sample ID	MIN	MAX	AVG
6-1	88.6	95.0	91.8	6-1	89.6	94.2	91.9
6-2	88.8	92.5	90.7	6-2	88.2	92.3	90.3
6-3	89.7	93.6	91.7	6-3	88.2	93.2	90.7

0.5 Meter

"A" Connector				"B" Connector			
Sample ID	MIN	MAX	AVG	Sample ID	MIN	MAX	AVG
6-1	86.7	93.0	89.9	6-1	86.7	92.8	89.8
6-2	86.9	98.8	92.8	6-2	86.4	98.3	92.4
6-3	87.6	97.3	92.5	6-3	86.1	98.2	92.2

PROJECT NO.: 200016	SPECIFICATION: USB 2.0
PART NO.: none	PART DESCRIPTION: cable
SAMPLE SIZE: 3	TECHNICIAN: MOB
START DATE: 9-18-00	COMPLETE DATE: 9-27-00
ROOM AMBIENT: 21 °C	RELATIVE HUMIDITY: 64 %
EQUIPMENT ID#: 473,474,1118,1157,1158	

SIGNAL PAIR ATTENUATION

PURPOSE:

1. The purpose of this test is to ensure that adequate signal sternest is presented to the receiver to maintain a low error rate

---

PROCEDURE:

1. The test was performed in accordance with EIA 364, Test Procedure 101.

2. Test Conditions:

   Frequency Range : 200 to 400 Mhz

REQUIREMENTS:
The signal pair attenuation shall not be more than the values shown for the test frequencies in the table below.

Frequency Mhz	db maximum
.512	0.13
.772	0.15
1.0	0.20
4.0	0.39
8.0	0.57
12.0	0.67
24.0	0.95
48.0	1.35
96.0	1.90
200.0	3.20
400.0	5.80

RESULTS:

1. All test units met the requirements specified.

2. The following is a summary of the data observed in db:

5 METER

	Sample ID – "A" Connector		
Frequency	MAX	MIN	AVERAGE
.512	.184	.171	.181
.772	.236	.230	.232
1.0	.274	.266	.269
4.0	.538	.524	.530
8.0	.747	.729	.737
12.0	.900	.881	.890
24.0	1.10	1.08	1.10
48.0	1.42	1.39	1.41
96.0	1.92	1.89	1.91
200.0	2.84	2.76	2.81
400.0	4.00	3.98	3.99

	Sample ID – "B" Connector		
Frequency	MAX	MIN	AVERAGE
.512	.176	.173	.175
.772	230	.225	.227
1.0	.267	.262	.265
4.0	.532	.523	.528
8.0	.739	.727	.734
12.0	.884	.871	.878
24.0	1.10	1.07	1.08
48.0	1.41	1.38	1.39
96.0	1.90	1.87	1.88
200.0	2.80	2.77	2.76
400.0	4.25	4.21	4.23

4 METER

	Sample ID – “A” Connector		
Frequency	MAX	MIN	AVERAGE
.512	.140	.138	.139
.772	.182	.180	.182
1.0	.212	.210	.212
4.0	.418	.417	.417
8.0	.583	.581	.582
12.0	.721	.714	.718
24.0	.866	.854	.861
48.0	1.12	1.10	1.12
96.0	1.53	1.50	1.52
200.0	2.29	2.26	2.28
400.0	3.53	3.47	3.51
	Sample ID – “B” Connector		
Frequency	MAX	MIN	AVERAGE
.512	.142	.132	.138
.772	.184	.180	.182
1.0	.214	.183	.202
4.0	.420	.417	.418
8.0	.584	.583	.584
12.0	.721	.719	.720
24.0	.867	.863	.864
48.0	1.13	1.12	1.12
96.0	1.52	1.52	1.52
200.0	2.27	2.28	2.28
400.0	3.48	3.48	3.52

3 METER

	Sample ID – “A” Connector		
Frequency	MAX	MIN	AVERAGE
.512	.104	.104	.104
.772	.137	.136	.137
1.0	.162	.159	.159
4.0	.314	.310	.312
8.0	.437	.431	.434
12.0	.546	.537	.540
24.0	.687	.674	.681
48.0	.874	.854	.862
96.0	1.17	1.14	1.16
200.0	1.78	1.73	1.75
400.0	2.77	2.74	2.75

	Sample ID – “B” Connector

Frequency	MAX	MIN	AVERAGE
.512	.130	.102	.112
.772	.136	.135	.136
1.0	.160	.158	.159
4.0	.313	.309	.311
8.0	.436	.427	.431
12.0	.543	.530	.536
24.0	.684	.664	.675
48.0	.871	.838	.855
96.0	1.16	1.12	1.14
200.0	1.77	1.70	1.74
400.0	2.76	2.70	2.73

2.5 METER

	Sample ID – "A" Connector		
Frequency	MAX	MIN	AVERAGE
.512	.087	.086	.086
.772	.114	.113	.114
1.0	.134	.132	.133
4.0	.261	.256	.259
8.0	.360	.353	.357
12.0	.446	.437	.442
24.0	.598	.587	.592
48.0	.719	.705	.710
96.0	.988	.958	.974
200.0	1.52	1.46	1.49
400.0	2.38	2.28	2.33

	Sample ID – "B" Connector		
Frequency	MAX	MIN	AVERAGE
.512	.087	.085	.086
.772	.114	.112	.113
1.0	.134	.131	.133
4.0	.263	.258	.260
8.0	.365	.357	.360
12.0	.452	.443	.447
24.0	.606	.592	.600
48.0	.728	.704	.719
96.0	.996	.957	.982
200.0	1.52	1.40	1.48
400.0	2.37	2.20	2.31

2 METER

	Sample ID – “A” Connector		
Frequency	MAX	MIN	AVERAGE
.512	.073	.070	.071
.772	.095	.092	.094
1.0	.111	.109	.110
4.0	.216	.212	.214
8.0	.297	.288	.294
12.0	.366	.350	.359
24.0	.526	.497	.512
48.0	.610	.554	.582
96.0	.854	.755	.800
200.0	1.36	1.11	1.22
400.0	2.19	1.86	1.98

	Sample ID – “B” Connector		
Frequency	MAX	MIN	AVERAGE
.512	.072	.070	.071
.772	.094	.092	.093
1.0	.111	.109	.110
4.0	.217	.210	.214
8.0	.297	.293	.293
12.0	.362	.357	.357
24.0	.516	.509	.509
48.0	.591	.576	.576
96.0	.807	.785	.786
200.0	1.25	1.19	1.19
400.0	1.99	1.92	1.92

1 METER

	Sample ID – “A” Connector		
Frequency	MAX	MIN	AVERAGE
.512	.036	.032	.034
.772	.047	.043	.045
1.0	.055	.052	.053
4.0	.105	.103	.104
8.0	.144	.139	.414
12.0	.170	.162	.164
24.0	.264	.250	.255
48.0	.311	.297	.302
96.0	.432	.411	.418
200.0	.693	.651	.668
400.0	1.09	1.08	1.08

	Sample ID – “B” Connector		

Frequency	MAX	MIN	AVERAGE
.512	.072	.070	.071
.772	.047	.043	.045
1.0	.055	.052	.053
4.0	.106	.103	.104
8.0	.144	.141	.142
12.0	.169	.167	.168
24.0	.263	.257	.261
48.0	.319	.305	.313
96.0	.446	.418	.435
200.0	.716	.671	.698
400.0	1.19	1.09	1.12

0.5 METER

	Sample ID – “A” Connector		
Frequency	MAX	MIN	AVERAGE
.512	012	.016	.017
.772	.023	.021	.022
1.0	.027	.025	.026
4.0	.054	.051	.052
8.0	.071	.069	.070
12.0	.083	.079	.081
24.0	.127	.118	.121
48.0	.162	.114	.142
96.0	.215	.174	.193
200.0	.469	.394	.438
400.0	.807	.683	.761

	Sample ID – “B” Connector		
Frequency	MAX	MIN	AVERAGE
.512	.018	.016	.017
.772	.023	.022	.022
1.0	.027	.025	.026
4.0	.052	.051	.052
8.0	.073	.069	.072
12.0	.086	.082	.084
24.0	.131	.127	.129
48.0	.172	.165	.169
96.0	.237	.211	.226
200.0	.525	.455	.493
400.0	.906	.773	.841

PROJECT NO.: 200016	SPECIFICATION: USB 2.0
PART NO.: none	PART DESCRIPTION: cable
SAMPLE SIZE: 3	TECHNICIAN: MOB
START DATE: 9-19-00	COMPLETE DATE: 9-28-00
ROOM AMBIENT: 22 °C	RELATIVE HUMIDITY: 52 %
EQUIPMENT ID#: 475,1118,1147,1148	

PROPOGATION DELAY

PURPOSE:

1. To determine the Propagation Delay of the transmission system under test.

PROCEDURE:

1. The test was performed in accordance with EIA 364, Test Procedure 103.

2. Test Conditions:

   Rise Time : 200 ps

REQUIREMENTS:

The propogation delay shall not exceed 5.2 nanoseconds per meter. (26nS max for a 5 meter cable)

RESULTS:

The following is a summary of the data observed in nanoseconds: (5. 2 nS/ meter max)

SIDE A

	Length in Meters						
Sample ID	5.0	4.0	3.0	2.5	2.0	1.0	0.5
6-1	26.1	20.8	15.5	13.0	10.4	5.1	2.5
6-2	25.8	25.8	15.5	12.8	10.3	5.0	2.5
6-3	26.2	26.2	15.5	12.9	10.3	5.1	2.5

SIDE B

	Length in Meters						
Sample ID	5.0	4.0	3.0	2.5	2.0	1.0	0.5
6-1	26.1	20.8	15.5	13.0	10.4	5.1	2.5
6-2	25.8	20.7	15.5	12.8	10.3	5.0	2.5
6-3	26.2	20.7	15.5	12.9	10.3	5.1	2.5

PART NO.: none	PART DESCRIPTION: cable
SAMPLE SIZE: 3	TECHNICIAN: MOB
START DATE: 9-19-00	COMPLETE DATE: 9-28-00
ROOM AMBIENT: 22 °C	RELATIVE HUMIDITY: 52 %
EQUIPMENT ID#: 475,1118,1147,1148	

PROPOGATION DELAY SKEW

PURPOSE:

1. To determine the Propagation Delay Skew of the transmission system under test. This will verify that the signal applied to the transmission lines arrives at the transceiver within the allocated time budget.

PROCEDURE:

1. The test was performed in accordance with EIA 364, Test Procedure 103.

2. Test Conditions:

   Rise Time : 200 ps

REQUIREMENTS:

The propogation delay skew shall not exceed 100 pS.

RESULTS:

The following is a summary of the data observed in picoseconds:

SIDE A

	Length in Meters						
Sample ID	5.0	4.0	3.0	2.5	2.0	1.0	0.5
6-1	11.2	19.3	18.2	13.3	1.7	5.6	1.5
6-2	15.1	10.0	11.4	3.8	0.9	4.2	10.0
6-3	4.6	.02	4.9	4.7	6.2	6.2	6.2

SIDE B

	Length in Meters						
Sample ID	5.0	4.0	3.0	2.5	2.0	1.0	0.5
6-1	21.6	17.2	23.8	15.5	0.6	20.5	0.2
6-2	2.5	12.4	22.0	7.5	20.5	7.2	6.1
6-3	7.4	12.3	19.2	1.3	2.6	4.3	0.9

PART NO.: none	PART DESCRIPTION: cable
SAMPLE SIZE: 2	TECHNICIAN: LP
START DATE:	COMPLETE DATE:
ROOM AMBIENT: °C	RELATIVE HUMIDITY: %
EQUIPMENT ID#: 140	

CAPACITIVE LOAD

PURPOSE:

To ensure that the distributed inter-wire capacitance is less than the lumped capacitance specified by the Low-speed transmit driver.

PROCEDURE:

1. The test was performed in accordance with USB 2.0.

2. Test Conditions:

Frequency : 100 Khz

REQUIREMENTS:

The capacitance shall between 200 and 450 pF.

RESULTS:

1. The following is a summary of the observed data in picofarads:

SIDE A

	Length in Meters						
Sample ID	5.0	4.0	3.0	2.5	2.0	1.0	0.5
6-1	270.0	217.3	165.8	136.8	112.8	57.7	30.7
6-2	274.2	218.8	165.4	139.5	111.8	57.1	30.5
6-3	270.4	21.83	166.4	137.6	111.1	57.8	31.0

SIDE B

	Length in Meters						
Sample ID	5.0	4.0	3.0	2.5	2.0	1.0	0.5
6-1	274.9	218.3	163.9	138.2	111.2	57.6	30.7
6-2	270.8	217.8	166.4	138.7	111.4	57.0	30.1
6-3	269.3	217.5	165.8	137.8	110.6	58.2	31.1

PART NO.: none	PART DESCRIPTION: cable
SAMPLE SIZE: 2	TECHNICIAN: LP
START DATE: 10-21-00	COMPLETE DATE: 10-21-00
ROOM AMBIENT: °C	RELATIVE HUMIDITY: %
EQUIPMENT ID#: see below	

SHIELDING EFFECTIVENESS

PURPOSE:

To determine the electromagnetic emission profiling and susceptibility of fabricated cable assemblies.

PROCEDURE:

1. The test was performed in accordance with USB 2.0 and EIA 364, test procedure 66.

2. Test Conditions:

Frequency Range	30MHz to 1 GHz
Number of Discreet Points	13
Mated/ Unmated	Unmated
Matching Impedance	50 ohm
Signal Generator Frequency	30 MHz
Signal Generator output above background noise	70 dB

REQUIREMENTS:

The minimum attenuation between 30 MHz and 1 GHz shall be 20 dB.

RESULTS:

The following is a summary of the data observed:

	Shielding Effectiveness (dB)				
Frequency MHz	6-1	6-2			
30	57.6	59.1			
50	78.1	66.0			
70	68.0	52.5			
100	58.4	60.4			
200	59.3	58.5			
300	42.5	35.9			
400	54.2	44.2			
500	39.7	54.3			
600	46.6	58.6			
700	50.8	61.7			
800	52.9	60.9			
900	48.7	50.5			
1000	49.8	55.6			

CALIBRATION: (National Technical Systems, Fullerton, CA)

Description	Model #	Control #	Cal. Due
HP Spectrum Analyzer	8566B	E4985F	01-28-01
HP Signal Generator	8673C	D5145F	06-08-01
IFI RF Amplifer	SMX 100	E4250F	N/A
Ailtech Biconical Antenna	94455-1	E4872F	09-06-01
Singer Log Spiral Antenna	93490-1	E4873F	04-21-01